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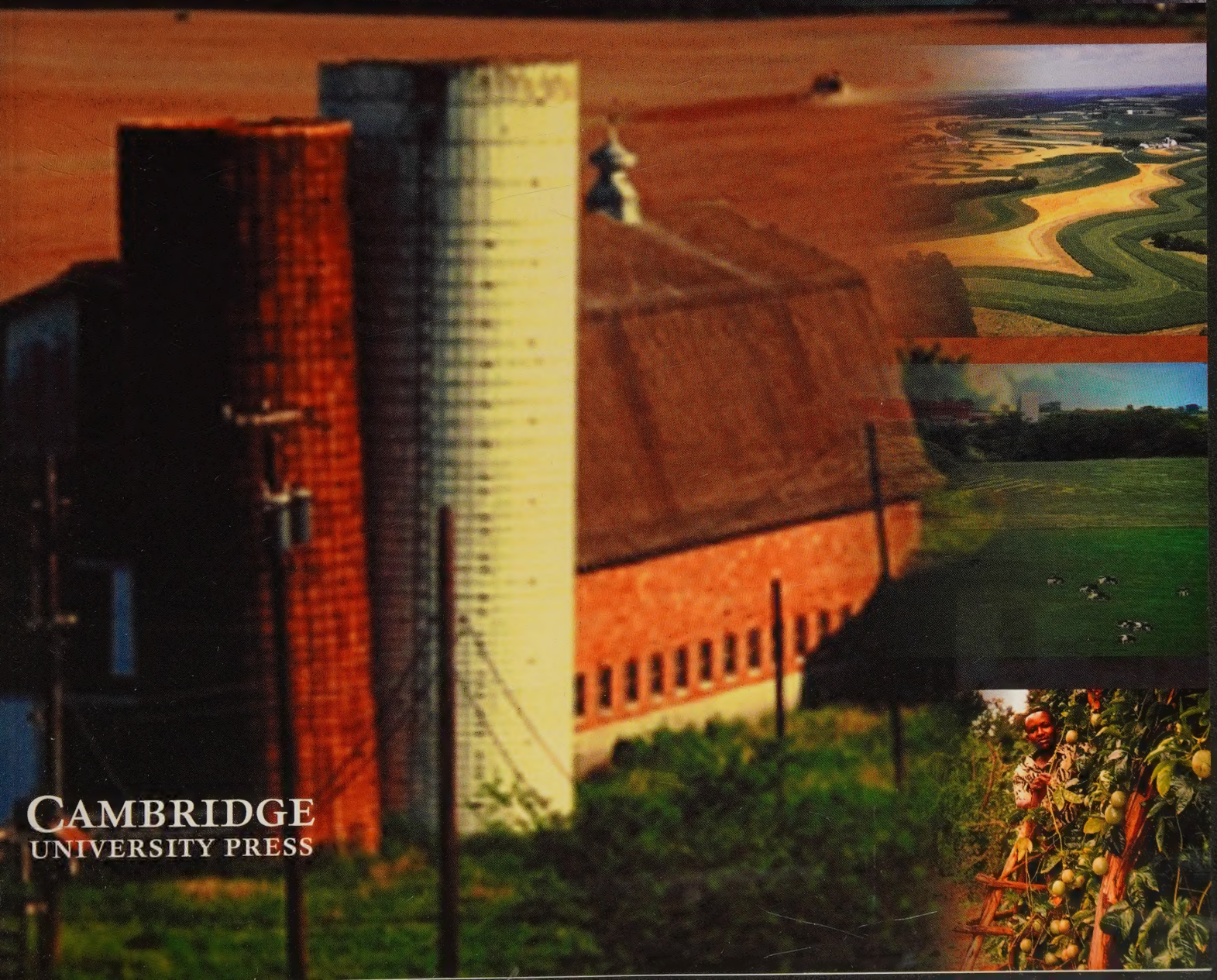

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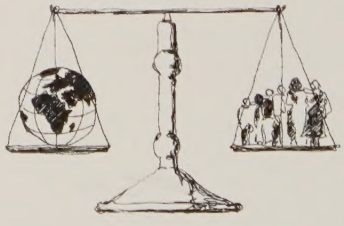

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Energy efficiency in small-scale biointensive organic onion production in Pennsylvania, USA

Stephen R. Moore*

The Center for Environmental Farming Systems, Department of Crop Science, North Carolina State University, Raleigh, NC, USA
*Corresponding author: steve_moore@ncsu.edu

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Abstract

Modern agriculture relies heavily on fossil energy for food production. Reducing fossil energy and replacing that energy with renewable energy is critical in attaining a sustainable food system. Hand-scale intensive food production offers a reduction in fossil energy and an increased use of renewable human-based energy. Using biointensive production techniques, onions (*Allium cepa*) were grown in Pennsylvania, USA. A life-cycle analysis was performed to monitor energy utilization. Individual human labor tasks were evaluated using the factor method. This method accounts for the type and duration of physical activity. The average yield of eight onion varieties utilizing biointensive production in standard-sized beds (9.3 m^2;100 ft^2) was 160.2 kg. The US average for mechanical onion production is 46.1 kg/9.3 m^2 (100 ft^2). The energy efficiency ratio, specific energy and energy productivity were 51.5, 0.03 MJ kg^{-1} and 32.2 kg MJ^{-1} (MJ = megajoule), respectively. When defined within common boundaries, these three relationships: energy input, energy output and yield productivity allow researchers, farmers and policy-makers to select production systems and/or practices that better manage fossil and renewable energy for food production. Current mechanized agriculture has an energy efficiency ratio of 0.9. With most energy being supplied by fossil fuels. The energy efficiency for biointensive production of onions in our study was over 50 times higher than this value (51.5) and 83% of the total energy required is renewable energy. Biointensive production offers a viable energy use alternative to current production practices and may contribute to a more sustainable food system.

Key words: biointensive, energy efficiency, organic, onion, manual production

Introduction

Modern food production shows signs of production stagnation, resource depletion and stress on the environment. To attain a sustainable food system will require increased intensification of land use, improved energy efficiency/productivity and increased use of renewable energy. The efficient utilization of energy in agriculture will lessen negative impacts on the environment[1–3], reduce demands on natural resources and increase sustainability within food production[3]. Current food production practices rely heavily on fossil energy for production. It is estimated that 13 units of fossil energy are required to produce 1 unit of food energy[4]. One strategy for improving energy utilization is to minimize machinery and rely more heavily on human labor[1,5,6].

Historically, many cultures (i.e., Chinese, Greek and Mayan) have relied on human labor and biologically intensive (biointensive) production practices. These practices have currently been developed and refined to include deep soil preparation (60 cm), close plant spacing and the utilization of on-farm produced compost crops to aid in sustaining soil fertility[7–10].

Biointensive farms are small by design. Small farms have the well-established advantage of an inverse relationship of size to productivity[11]. Also, biointensive production practices utilize deep soil (similar to sub-soil like) techniques similar in deep soil preparation which have reported yield increases of up to 63% over shallower tillage practices[12].

Biointensive production practices allow for detailed and specific on-farm data collection and review. Farm-level

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Figure 1. Biointensive production of onions, Pennsylvania, USA, 2004.

data provide important and specific information for a given farm. Repeated over several farms and crop types, farm data can also support more generalized conclusions. Farm-level data provide the ability to test combinations of inputs and techniques, to judge energy efficiencies of potential combinations of inputs and to isolate the most important elements that affect energy efficiency[13].

It is important to establish commonalities in the evaluation of energy flow to minimize disparities in reporting and subsequent difficulties in comparing energy balance conclusions. One important part of this standardization is similar system boundaries[13]. System boundaries and commonalities allow researchers, farmers and policy-makers to compare energy data.

The push away from fossil energy dependence and pull toward a more sustainable food system is important for producers and society in general. Increasingly refined accounting will be needed to evaluate individual components of production. This preliminary study offers a task-oriented evaluation of human labor, with specific considerations for gender, age, weight and climate. The embodied energy of specific tools used in biointensive small-scale food production was calculated. Onions (*Allium cepa*) were the vegetable crop chosen for the study.

Materials and Methods

Location, soils and climate

This study was conducted in 2004 at Sonnewald Natural Foods, Spring Grove, York County, Pennsylvania, USA; latitude 39.8744, longitude −76.8646 and elevation 135 m (443 ft). Climatically, Spring Grove has an average winter temperature of −0.2°C (31.6°F) and an average summer temperature of 22.6°C (72.6°F), with a relative humidity of 53%. Precipitation averages 1016 mm (40 inches) of rain with 53% falling between May and October. Seasonal snow averages 802.6 mm (31.6 inches). Sunshine is available 67% of the possible time in the summer and 50% of the possible time in the winter[14].

Figure 2. Biointensive production of Alisa Craig onions (coin is 2.4 cm in diameter) Pennsylvania, USA, 2004.

The soils are part of the Manor/Mt Airy series. This is a coarse–loamy, micaceous, mesic Typic Dystrochrepts. It consists of very deep, somewhat excessively drained soils on ridge tops, side slopes and hillsides on dissected uplands. These soils formed in channery material weathered from residuum, schist and phyllite[14]. The research area had a < 3% slope (westerly). Organic soil practices had been in use for 50 years. The area of specific research had been utilized for 3 years for vegetable production, prior to that it had been in sod for ~8 years. For the 3 years previous to this study, annual applications of compost (composed of municipal leaves and horse manure) were applied, resulting in a soil organic matter (SOM) content of ~5%. Weeds had been controlled for 3 years with annual cover crops, stale seed beds and weed management during cropping cycles.

Biointensive production method and related tools

Utilizing biointensive crop production principles[7,8], permanent beds and pathways, 1.5 m (5 ft) and 0.3 m (1 ft) wide, respectively, were established 3 years prior to this study. These beds ran approximately north to south. The soil had been prepared to a depth of 0.6 m (2 ft) using a double-digging hand-tillage technique[8] for 3 years prior to this study. For this production cycle, a U-bar was utilized for bed soil tillage. A U-bar is a fabricated metal broad fork (built by the author) with nine 0.5 m (19 inch) steel tines and two 1.6 m (61.5 inch) long handles. The U-bar is 74 cm (29 inches) wide, allowing two side-by-side passes to till the 1.5 m wide bed. The user stands on the tine support bar and rocks the tines into the soil. Utilizing the operator's weight, the operator leans back resulting in the upward movement of the tines through the soil, providing quick and thorough primary hand tillage. Following U-bar treatment, the bed was then raked.

Table 1. Activity levels and MJ burned per individual worker for farming/gardening tasks, with adjustment for gender.

	Farming/gardening activity			
	Very light work (1)	**Light work (2)**	**Moderate work (3)**	**Heavy work (4)**
	Seeding Watering Broadcast Seeding	Harvesting Hauling (light) Weeding (light) Raking Hoeing (light) Transplanting	U-baring (light) Hauling (heavy) Hoeing (heavy) Scything Sifting compost Turn pile	U-baring Double digging
$MJ\,kg^{-1}\,h^{-1}$				
Male	0.006	0.012	0.018	0.035
Female	0.005	0.011	0.017	0.034
$MJ\,h^{-1}\,laborer^{-1}$				
Male 86.5 kg (190 lb)	0.519	1.038	1.557	3.028
Adjusted for age 53 (10%)	0.467	0.934	1.399	2.725
Female 56.8 kg (125 lb)	0.284	0.625	0.966	1.931

Onion production

Eight onion (*A. cepa*) varieties (Alisa Craig, Grex, Super Star, Clear Dawn, New York Early, Siskiyou Sweet, Prince and Delgado) were hand sown on 15 January in wooden flats, $59 \times 36 \times 7.6\,cm^3$ ($23 \times 14 \times 3\,inch^3$). Each flat contained mesophilic compost as a growing medium. This compost was produced on the farm. Twenty rows were made along the width of the flat. Each row was approximately 1.3 cm (0.5 inch) deep. Approximately 30 seeds were planted and covered in each row. This technique yields approximately 20 plants row^{-1} and 400 plants $flat^{-1}$. At 15–20 cm (6–8 inches) in height, one-third of the onion plant tops were removed. This was repeated three times. Trimming the tops of the onions helps to create stockier transplants that are more durable and increase the survival rate. Seedlings were raised in a compost-heated high tunnel (greenhouse structure without any direct supplemental heat). No accounting of heat energy generated from the compost or the embodied energy of the high tunnel was included in this study. Plants were hardened off in early April. Transplanting was done 8–12 April on 15 cm (6 inch) offset center spacings yielding 621 plants per bed (see Figs. 1 and 2). The unit 'bed' is described as $1.5\,m \times 6.15\,m = 9.2\,m^2$ ($5\,ft \times 20\,ft = 100\,ft^2$). Three manual weed control hoeings were performed utilizing a 12 cm (5 inch) wide trapezoid hoe (Johnny's Selected Seeds, item no. 9589). Mesophilic compost (produced by author) was added at the rate of $0.15\,m^3$ ($4\,ft^3$) per bed. No additional soil amendments, insect or disease management was necessary (see Fig. 2). When the onions reached maturity, ~50% water content, the tops were laid flat with the back of the garden rake. Onions were harvested 9–14 June by hand, placed in a two-wheeled handcart and weighed. Yield data were collected at this point. The onions were cured and stored for market sales.

Assessing energy expenditure

Human labor. It is a challenge to evaluate human labor energy expenditures. One of the most accurate methods is the metabolic cost as measured by either oxygen consumption or doubly labeled water isotopes[15]. These methods are impractical for on-farm evaluations due to expense and complexity. The factorial method accounts for energy expenditures by recording the type and duration of physical activities[15]. The factorial method was utilized in this study.

Tasks performed by human labor were divided into four energy activity levels[16,17] (Table 1). These four activity levels are: very light work, light work, moderate work and heavy work (assigned numbers 1, 2, 3 and 4, respectively). Farm-related work was established within each level, based on the author's 30 years of vegetable production experience. The energy output of these activity levels was adjusted for gender, age and environmental influences (Table 1). These factors were used to establish values of $MJ\,h^{-1}$ activity level (or task)$^{-1}$ individual $worker^{-1}$.

Gender affects energy expenditure. Females utilize 7–10% less energy to perform the same task per body mass as their male counterparts[15–17]. Gender was accounted for among the specific laborers for this study.

Environmental influences have been shown to affect the amount of energy consumed per activity[15,16]. Environmental temperatures $\geqslant 37°C$ (99°F) result in increased energy requirements for human labor[17]. Research also indicates that a cold environment $\leqslant 14°C$ (57°F) can result in a 5% greater energy cost for labor[15]. In addition to temperature, altitude can make a difference in energy expenditure. This study was conducted well below 'high altitude'[15]. Daily high and low temperatures and altitude adjustments to the $MJ\,h^{-1}$ for human labor were not

Table 2. Embodied energy of tools and equipment used in biointensive onion production.

Tools	Steel (kg)	Steel embodied energy/tool (MJ kg^{-1})	Useful life of steel (years)	Steel embodied energy per year (MJ)	Lumber (kg)	Lumber embodied energy/tool (6 MJ kg^{-1})	Useful life of lumber (years)	Lumber embodied energy per year (MJ)	Total embodied energy per tool per year (MJ yr^{-1})	Tool use per bed yr^{-1} or farm yr^{-1}	Total number of times the tool is used per bed year^{-1}	MJ per bed, use or h
Cart, two wheel	27.4	848.3	30.0	28.3	15.4	92.2	15.0	6.1	34.4	1 h day^{-1}	1 h day^{-1}	0.09 MJ h^{-1}
Shovel, pointed or flat	1.1	35.2	25.0	1.4	0.7	4.1	10.0	0.4	1.8	3 h wk^{-1}	156 h yr^{-1}	0.01 MJ h^{-1}
U-bar	22.5	697.5	25.0	27.9	0.0	0.0	20.0	0.0	27.9	400 beds	80% × 500beds	0.07 MJ bed^{-1}
Rake, garden steel	0.8	24.7	25.0	1.0	0.6	3.4	10.0	0.3	1.3	3 h wk^{-1}	156 h yr^{-1}	0.01 MJ h^{-1}
Hoe, trapezoid	0.4	12.0	5.0	2.4	0.6	3.4	10.0	0.3	2.7	3 h wk^{-1}	156 h yr^{-1}	0.02 MJ h^{-1}
Flat wood	0.0				2.7	16.4	8.0	2.0	2.0	10 times yr^{-1}	10 times yr^{-1}	0.2 MJ use^{-1}

warranted as those influences were under the values for increased energy expenditures and corresponding adjustments.

The age of the laborer affects energy expenditure per task[17]. The male laborer for this study was 53 years old and required 10% less energy to perform each task[16]. The female worker was under 50 years old and required no energy expenditure adjustment.

Non-labor energy. Embodied energy was determined for each tool. Values for the embodied energy varied from 27.72 to 35 MJ kg^{-1} for steel, and from 2.8 to 18.9 MJ kg^{-1} for lumber[18,19]. For this study, the following values were used for the embodied energy of steel and lumber 31 and 6 MJ kg^{-1}, respectively[20]. Several criteria were used in determining a final value for the embodied energy in a tool; these included useful life (years), component weight of tool (kg), number of times a tool was used per year, prorated for each use and hours-of-use per bed. This information was collated and calculated in Table 2.

Irrigation utilized overhead impulse sprinklers from a tube well. Three applications of 2.5 cm (1 inches) of irrigation water (0.697 m^3 bed^{-1}) were applied at an energy cost of 0.63 MJ m^{-3},[21,22] for a total calculated energy input of 0.439 MJ bed^{-1}.

Compost was produced on site. Using biointensive techniques[7], comfrey (*Symphytum tuberosum*), corn (*Zea mays*) and alfalfa (*Medicago sativa*) were raised on 1, 2.6 and 0.85 beds, respectively. This combination totals 4.45 beds and produced 1.44 m^3 (50.7 ft^3) of cured compost. An energy flow and utilization chart (see Fig. 3) accounts for task use and expenditure of energy for the various tasks associated with compost production. Accounting was performed using an input/output analysis similar to that used for onions (see Table 3). The embodied energy of compost was calculated at 9.5 MJ m^{-3}.

Table 3, input and output energy, integrates the embodied energy of tools, irrigation, compost and labor to determine the input energy and calculates the energy ratio (output/input energy).

Based on the input and output energy (Table 3) and yield data, energy balance indicators were calculated using the following equations[22–24]:

$$\text{Energy ratio (ER)} = \frac{\text{Energy output (MJ bed}^{-1})}{\text{Energy input (MJ bed}^{-1})}, \quad (1)$$

$$\text{Specific energy} = \frac{\text{Energy input (MJ bed}^{-1})}{\text{Onion output (kg bed}^{-1})}, \quad (2)$$

$$\text{Energy productivity} = \frac{\text{Onion output (kg bed}^{-1})}{\text{Energy input (MJ bed}^{-1})}. \quad (3)$$

Not all input energy expenditures were included in this study. Only anthropocentric energy inputs were used for this analysis; hence the input energy from the sun was not used in these calculations, neither was the embodied energy of onion seeds.

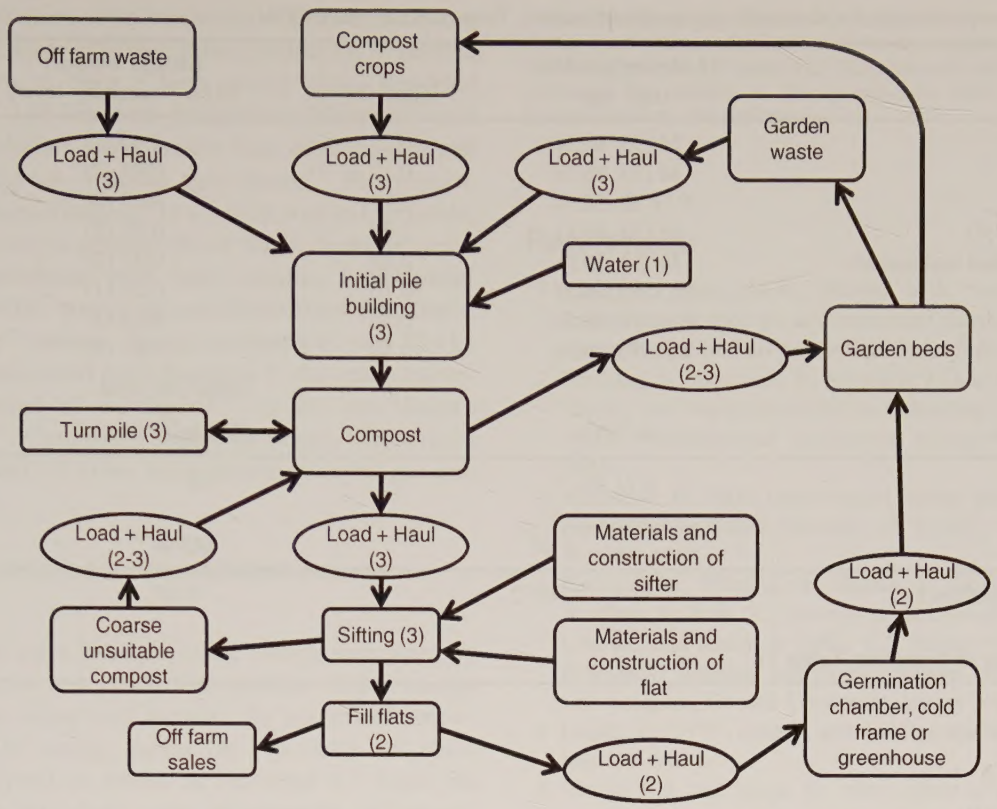

Figure 3. Flow of energy in compost production and utilization, numbers in parentheses indicate activity levels shown in Table 1.

Results and Discussion

Energy input

Human labor accounted for 3.05 MJ bed^{-1} and 62% of the total energy inputs (Table 3). Taking the average of the four activity levels for men resulted in an average energy output of 1.5 MJ h^{-1}. This is very similar to the reported general labor value of 1.58 MJ h^{-1} used by Liu[23]. Values of 2.3 MJ h^{-1} and 1.96 MJ h^{-1} have also been reported[3,24]. Norman[25] reported an energy expenditure for hoeing of 1.15 MJ h^{-1}. This is comparable to the value used for hoeing in this study for a male (53 years old, 86.5 kg) of 0.93 MJ h^{-1}. These comparisons show that the specific energy accounting used in this study was consistent with previous research work.

The input energy expenditure for compost, irrigation and the embodied energy of the tools were 1.05, 0.44 and 0.40 MJ bed^{-1}, respectively. The percent of energy expended by type of input is shown in Figure 4. Human labor and compost are primarily renewable energy and combined, contribute to a renewable energy input of 83%. No studies were found that accounted for energy balancing in hand-scale production of compost crops and subsequent compost production. For comparison, compost produced mechanically with fossil energy had an embodied energy of 1091–8817 MJ m^{-3} (adapted from Brinton[26]).

Energy output

Yield values are important considerations in energy output determination. In this study, onion yields were recorded in Table 4. The average yield was 160.2 kg bed^{-1} and that of the highest yielding variety was 205.6 kg bed^{-1}, a 348% increased yield over the US average (46.1 kg bed^{-1})[8,27] for the average onion yield and a 446% increase for the highest yielding variety. This yield is in line with other biointensive production data. Other biointensive tests have produced onion yields of 7.4 times (740%) the US average[7]. Although the study did not include onions, food production under intensive cultivation within the Biosphere II in Oracle, Arizona, showed a 216% increase in average yields over target amounts (conventional yields) for seven various legumes and starchy vegetables[9,28]. These data included a significant variation of yield over conventional production, with potato and cowpea 425% and squash and dry bean 90%. This variation over a single growing season shows both the potential in any given growing season and the possibility of crop loss and reduced yield. It should be noted that Holt and Smith[10] found no statistical difference between treatments of double digging/deep soil preparation (50 cm), single digging (25 cm) and surface cultivation (5–6 cm) in beets and bush bean yield. One difference in production techniques used by Holt and Smith and others cited was the lack of compost as an amendment.

Energy output was determined by multiplying yield values (Table 4) by the established value of 1.58 MJ kg^{-1} (172 Cal lb^{-1}) for fresh onions[29]. The resulting high yield energy output was 324.8 MJ bed^{-1} and the average energy output was 253.6 MJ bed^{-1}.

Table 3. Input–output energy for biointensively produced onions, Pennsylvania, USA, 2004.

Labor task	Laborer gender (age, kg)	Time (h)	Energy output: MJ h^{-1} (activity level)	MJ bed^{-1}
U-bar	M (53, 86.5)	0.25	1.40 (3)	0.35
Rake	M (53, 86.5)	0.17	0.93 (2)	0.16
Transplant	F (< 50, 56.8)	1.17	0.63 (2)	0.74
Hoe and weed (3 ×)	M (53, 86.5)	1.00	0.93 (2)	0.93
Compost (load, haul and spread)	M (53, 86.5)	0.25	0.93 (2)	0.23
Seeding flat	F (< 50, 56.5)	0.10	0.28 (1)	0.03
Seedling care	F (< 50, 56.5)	0.50	0.63 (2)	0.32
Harvest	F (< 50, 56.5)	0.50	0.63 (2)	0.32
			Labor sub-total	3.08
Soil amendments	**m^3 (ft^3)**		**MJ m^{-3}**	**MJ bed^{-1}**
Compost	0.11 (4)		9.5	1.05
Irrigation	**m^3**		**MJ m^{-3}**	**MJ bed^{-1}**
(3) 2.54 cm applications bed^{-1}	0.6972		0.63	0.44
Embodied energy of tools (see Table 2)				**MJ bed^{-1}**
Shovel				0.01
U-bar				0.07
Rake				0.01
Hoe				0.02
Big cart				0.09
Flat (wood)				0.20
			Tools sub-total	0.40
Input energy (MJ)				4.97
Output energy (MJ, average yield)				253.6
Energy ratio (average yield)				51.0

Table 4. Onion yield under biointensive production practices, Pennsylvania, USA, 2004.

Onion variety	Onion yield kg (lb)	Energy output MJ bed^{-1} (Cal bed^{-1})
Grex	205.6 (453.3)	324.8 (77,968)
Alisa Craig	174.7 (384.3)	276.8 (66,100)
Delgado	171.0 (376.3)	270.9 (64,724)
New York Early	160.9 (354.0)	254.9 (60,888)
Super Star	157.1 (345.6)	248.2 (59,443)
Siskiyou Sweet	155.3 (341.6)	246.1 (58,755)
Clear Dawn	149.6 (329.1)	237.0 (56,605)
Prince	107.3 (236.0)	170.0 (40,592)
Average	160.2 (352.5)	253.6 (60,630)

It should be noted that the total size of the planting was 20,000 onions. It is often noted that hand-scale production is primarily for subsistence. Onions, produced in these quantities offer opportunities to produce food on a small hand-scale in an efficient manner and contribute to feeding larger communities of people.

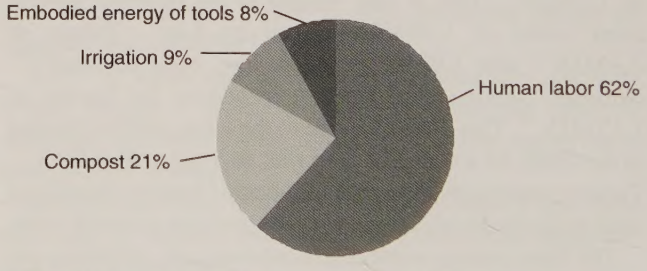

Figure 4. Input energy for biointensive onion production.

Energy balance indicators

The energy efficiency ratio (ER) was calculated using Equation 1 and found to be 51.0. No reported values for hand-scale production were found. In mechanical/fossil fuel-based production, an ER for onion production was 0.9[30]. This fossil energy based value only included input accounting for fuel and electrical energy, and excludes the embodied energy of the machinery/tools, human labor and soil amendments, whereas these are included in the biointensive production ER. Comparing these energy ratios indicates the significant energy conversion efficiency of

hand-scale production, with biointensive production being 57 times more energy efficient. Hand production in general has been shown to have a high energy ratio. Reported values include 128.2 in corn production (Mexico)[31] and mixed crops including sweet potato, taro, cassava, yam and banana (New Guinea, swidden agriculture)[32]. Biointensive energy conversion efficiency, in a 3-year trial in California, was shown to have a general ER of 50 (J. Todd, personal written correspondence with John Jeavons, 2 November 1973). The specific energy as calculated from Equation 2 was 0.03 MJ kg^{-1} onions. Energy productivity was 32.4 kg onions MJ^{-1}, calculated from Equation 3. An onion energy productivity value of 1.01 kg MJ^{-1} is the only known reported value[33]. Comparing these two values, biointensive practice produced 32 times more onions (weight) per unit of input energy.

Future opportunities for sustainable energy balancing

There are three ways to improve the energy sustainability of biointensive or any production systems: lower energy inputs, increase output and increase the percent of renewable energy. The energy inputs for this study are minimized. Output/yield of onions is increased 3.5 times per unit of area in this study using biointensive techniques. Energy output might be increased further by reducing plant spacing. This reduced spacing can increase overall yield (kg and MJ) per unit of area, but typically reduces individual plant yield and size. Utilizing a greater percentage of renewable energy—for water pumping, fertilizer and amendment production, and tool manufacturing and other related processes—can also contribute to a more sustainable food production system.

Conclusion

In order to attain a sustainable food system, it is important to maximize energy efficiency and utilize renewable energy throughout the system. Increasing the detailed accounting of energy flows directly and indirectly related to a method of food production can be used to compare and improve the energy efficiencies of our current food production systems. Small-scale hand production using biointensive techniques offers decreased reliance on fossil energy and a corresponding increase of renewable energy use. Onions produced in this manner showed a very high energy efficiency and corresponding energy productivity for the season during which this study took place. These levels of productivity and efficiency are typical, based on the author's many years of experience with biointensive production. Since only one season and one crop were analyzed, this study shows that research and development of energy-efficient tools and techniques, such as biointensive production, are justified and there is strong potential to improve the sustainability of our current and future food production systems.

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A rotation design to reduce weed density in organic farming

Randy L. Anderson*

USDA-ARS, Brookings, SD 57006, USA
*Corresponding author: randy.anderson@ars.usda.gov

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Abstract

Weeds are a major obstacle to successful crop production in organic farming. Producers may be able to reduce inputs for weed management by designing rotations to disrupt population dynamics of weeds. Population-based management in conventional farming has reduced herbicide use by 50% because weed density declines in cropland across time. In this paper, we suggest a 9-year rotation comprised of perennial forages and annual crops that will disrupt weed population growth and reduce weed density in organic systems. Lower weed density will also improve effectiveness of weed control tactics used for an individual crop. The rotation includes 3-year intervals of no-till, which will improve both weed population management and soil health. Even though this rotation has not been field tested, it provides an example of designing rotations to disrupt population dynamics of weeds. Also, producers may gain additional benefits of higher crop yield and increased nitrogen supply with this rotation design.

Key words: ecological processes, organic systems, systems design, weed population dynamics

Introduction

Weeds remain one of the major obstacles to successful crop production in organic farming, even though producers invest considerable resources to control weeds[1]. New implements, methods and organic herbicides are being developed for weed control[2,3]; yet, even with these additional options, yield losses due to weeds are still prominent.

Barberi[4], considering recent advances in methodology, questioned whether emphasis on specific control tactics was the most effective approach to manage weeds in organic systems. He speculated that the control tactic approach may neglect the systemic ('holistic') nature of organic agriculture, and encouraged researchers to consider system design in addition to control tactics. A similar suggestion was made by Bastiaans et al.[5] for conventional farming: a systems approach could be a key to successful weed management.

Our interest in system design is stimulated by a weed management approach used in the semi-arid Great Plains. Historically, producers in this region followed a winter wheat (*Triticum aestivum* L.)–fallow rotation and they tilled to control weeds during fallow. No-till practices, however, enabled producers to crop more frequently before needing fallow again. Crops such as corn (*Zea mays* L.), proso millet (*Panicum miliaceum* L.) and sunflower (*Helianthus annuus* L.) are now grown in rotations with winter wheat and fallow. With this diversity of crops, producers were able to design cropping systems that disrupted weed population dynamics, subsequently reducing herbicide inputs by 50% compared with conventional practices[6]. Less herbicide is needed because weed density in croplands declines across time.

To stimulate more consideration of the systems approach, Barberi[4] suggested that examples of system designs for weed management in organic farming be described in the scientific literature. In a similar perspective, Hill and McRae[7], analyzing various approaches to sustainable agriculture systems, found that a vital aspect of successful transitions to sustainable agriculture was designing cropping systems based on ecological principles rather than modifying existing systems in response to a specific issue.

Producers in the Great Plains improved weed management by designing cropping systems to disrupt population growth of weeds[8]. We speculate that weed management in organic rotations may also respond to rotation design, especially if the design is guided by principles of population ecology. Therefore, the purpose of this paper was to explain the systems approach used successfully by producers in the Great Plains, and then to suggest a rotation

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design for organic farming based on these principles. Our suggested rotation involves cropping practices prevalent in the western edge of the Corn Belt, but we believe these principles will also apply to other regions where different crops are grown.

A Population-Based Approach to Weed Management

Population-based weed management in the Great Plains involves cultural tactics that reduce weed seed survival in the soil seed-bank, suppress weed seedling emergence and minimize seed production of weeds that escape control. A pivotal factor in this approach is rotation design[9]. Rotations are arranged to include crops with different life cycles, such as winter wheat and corn. Weeds common in winter wheat, such as downy brome (*Bromus tectorum* L.), are easily controlled during the growing season of warm-season crops such as corn, thus eliminating seed production of downy brome in that year[9]. The lack of seed production along with the natural death of seeds across time reduces density of weed seeds in soil and, subsequently, number of weed seedlings in following years. A similar benefit occurs with warm-season weeds and cool-season crops.

However, the arrangement of cool- and warm-season crops in rotation is critical for weed population management[9]. This factor was demonstrated with three long-term rotation studies in the Great Plains. Rotations were comprised of various combinations of cool- and warm-season crops. Weed management was based on best management practices, yet weed community density varied eightfold among rotations after 10 years (Fig. 1). In all studies, the lowest weed density occurred in rotations comprised of two cool-season crops followed by two warm-season crops, whereas rotations comprised of one cool- and one warm-season crop had the highest weed density[6]. The 2-year intervals of crops with similar life cycles balance two factors of weed population dynamics: natural decline of weed seed density in soil across time and population growth rate of weeds during the cropping season[9]. The impact of balance between crop seasonal types was also noted with three-crop rotations, where weed density was threefold higher than with four-crop rotations (Fig. 1). Warm-season weeds proliferated with rotations comprised of two warm-season crops and one cool-season crop. Similarly, cool-season weeds were predominant in three-crop rotations that included two cool-season crops.

A further aspect of rotation design is crop diversity within a life-cycle category. For example, density of downy brome was 40 times higher in a four-crop rotation that included two winter wheat crops compared with the same rotation but where dry pea (*Pisum sativum* L.) replaced one winter wheat crop[8]. Planting dry pea in April provided an opportunity to eliminate downy brome seedlings in that year. A similar trend occurs with summer annual weeds; weed density is lower when summer annual crops with different planting dates are grown compared with growing the same crop 2 years in a row[8].

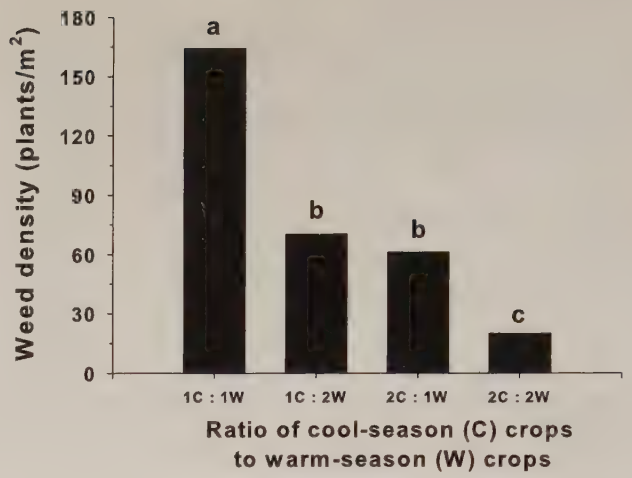

Figure 1. Weed community density among various rotation designs in the Great Plains. Abbreviations are: C, cool-season crop; W, warm-season crop. Cool-season crops were winter wheat, spring wheat or dry pea; warm-season crops were corn, soybean, sunflower, proso millet or chickpea (*Cicer arietinum* L.). Data averaged across three studies. Bars with the same letter are not significantly different as determined by Fishers' Protected LSD (0.05). (Adapted from Anderson[6].)

No-till practices also help weed management. This benefit was initially attributed to crop residues on the soil surface suppressing weed germination and seedling establishment, as weed seedling density is reduced approximately 15% for each 1000 kg/ha of residues[8]. But, no-till also increases mortality of weed seeds in the soil. Tillage buries weed seeds in soil, thus seeds are protected from environmental extremes and predation. In contrast, leaving weed seed on the soil surface with no-till leads to extensive loss of seed viability[10].

The impact of no-till on weed seed survival was shown in a series of studies that compared weed seedling emergence for 3 years in no-till and tilled treatments[8]. The sites were naturally infested with weeds, but after initiation of each study, further weed seed rain was prevented. Seedling emergence declined 70–95% by the third year compared with the first year (Fig. 2). But differences between no-till and tillage increased with time. In the first year, weed seedling emergence was similar between tilled and no-till, whereas in the second year the difference between tillage treatments was about twofold. In the third year, however, seedling emergence was eightfold greater with tillage. Because of this eightfold difference in the third year, no-till accentuates the effect of 2-year intervals of cool- and warm-season crops on weed dynamics.

The synergistic interaction between no-till and rotation design was demonstrated in the long-term cropping systems studies described above[6]. One site was no-till for the duration of the study whereas a second site was minimum-till, with one tillage operation by non-inversion implements occurring each year. First, weed density was fivefold higher

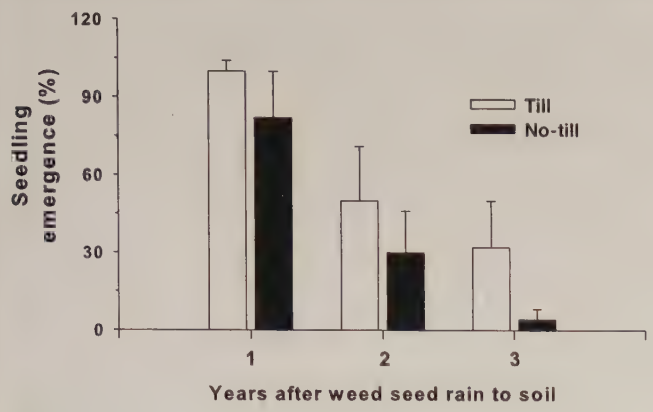

Figure 2. Impact of tillage on seedling emergence across time, averaged across four studies. Weed seeds were not added to the soil after initiation of the study; tillage occurred in the tilled treatment each year. Data expressed as a percentage of the treatment with the highest number of weed seedlings in each study. Standard error bars were derived from yearly means among studies. (Adapted from Anderson[8].)

at the tilled site compared with the no-till site, averaged across all rotations in each study. Second, the difference in weed density between four-crop rotations and two-crop rotations was greater in no-till. Weed density was 13-fold higher in two-crop rotations compared with four-crop rotations at the no-till site, but at the minimum-till site, the difference between rotation designs was only fivefold.

An additional factor of weed population ecology is productivity of weeds that establish in crops. Producers can reduce seed production of these plants by improving crop competitiveness with cultural tactics. Several tactics are available, such as increasing the seeding rate or choosing a taller cultivar, but effectiveness is enhanced by combining tactics together[8]. For example, a single cultural tactic with sunflower, such as narrower row spacing, higher plant population, or delayed planting, reduces seed production of redroot pigweed (*Amaranthus retroflexus* L.) 5–10% compared with the conventional system used by producers. When two tactics are combined, seed production is reduced 15–25%. However, seed production is reduced almost 90% when three tactics are integrated together. Similar trends occur with winter wheat, proso millet and corn; effective suppression of weed seed production requires that several cultural practices be used together[8].

Producer Experiences with Population-Based Weed Management

Producers are managing weeds with 50% less inputs with no-till rotations such as spring wheat–winter wheat–corn–sunflower or dry pea–winter wheat–corn–proso millet[6]. Herbicides are not needed in some crops because the low weed density does not affect crop yield. However, weed density has not declined in no-till rotations comprised of only one or two crops; herbicide use remains high with these rotations[6]. Successful population management of

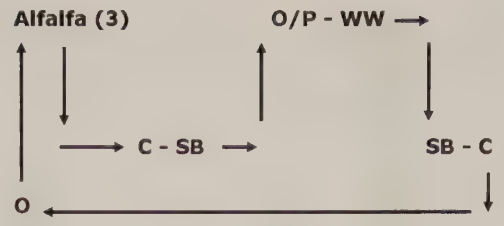

Figure 3. A rotation design that may suppress weed density in organic systems. The figure visually aligns cool-season crops in the upper part of the figure and places warm-season crops below. Abbreviations are: C, corn; SB, soybean; O/P, oat–pea mixture for forage; WW, winter wheat; and O, oat (grown as a companion crop for establishing alfalfa). The (3) refers to 3 years of alfalfa production.

weeds in the Great Plains requires the synergistic interaction of rotation design, crop diversity, no-till and competitive crop canopies[8].

A Population-Based Approach for Organic Rotations

We believe that organic producers can also reduce weed density and management inputs with a population-based approach, especially if rotations are extended to include perennial forages. As an example, we suggest a 9-year rotation consisting of 3 years of alfalfa, followed by a warm-season sequence of corn and soybean, a cool-season sequence of an oat (*Avena sativa* L.)/pea mixture for forage and winter wheat, a second warm-season interval of soybean–corn, and alfalfa re-established with oat as a companion crop (Fig. 3). Note that the rotation includes 2-year intervals of cool- and warm-season annual crops, and that crops within a life-cycle interval (i.e., cool- or warm-season crops) have different planting dates to provide an additional opportunity to control weed seedlings. Further weed management options are discussed within suggested sequences.

Interval of alfalfa

Population dynamics of weeds are disrupted in alfalfa due to both mowing for forage harvest and competitiveness of alfalfa; it is difficult for weeds to establish and produce seeds. Also, weed seeds remain on the soil surface during the alfalfa interval because the field is not tilled; consequently, weed seed survival declines rapidly across time, as noted in Figure 2. Three years of alfalfa is the most detrimental to weed population dynamics, with weed seedling density being only 10% in the third year compared with the first year (Fig. 4). Density of cool-season weeds adapted to alfalfa management, such as field pennycress (*Thlaspi arvense* L.), dandelion (*Taraxacum officinale* Weber in Wiggers) and downy brome, increase in the fourth and fifth year of alfalfa. Alfalfa competitiveness with weeds decreases in the later years because stand density of alfalfa declines across time[14,15].

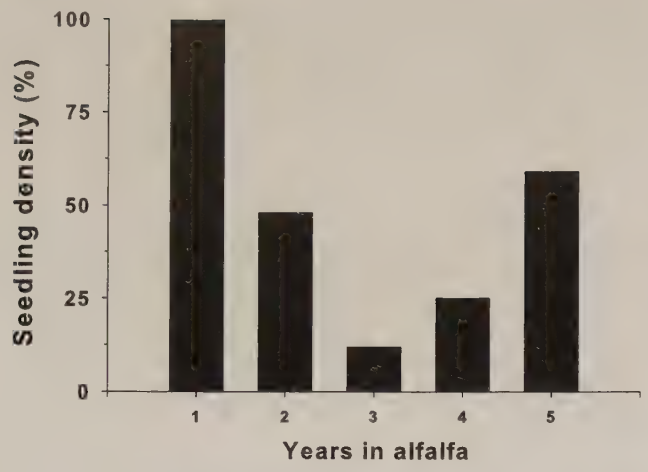

Figure 4. Seedling emergence of the weed community in alfalfa across time. Data are expressed as a percentage of highest emergence in the first year, and averaged across several studies. (Adapted from Harvey and McNevin[11], Entz et al.[12] and Ominski et al.[13].)

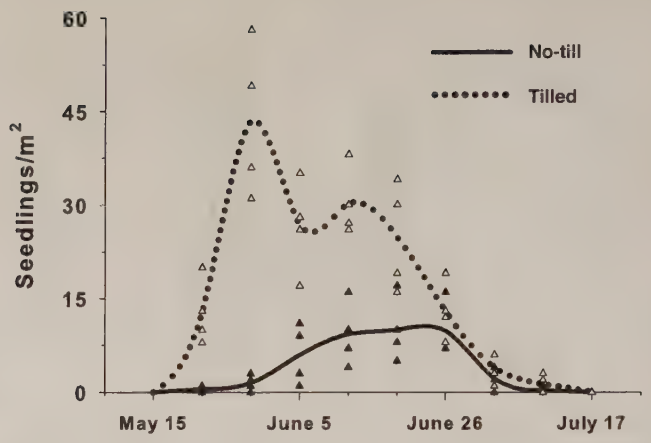

Figure 5. Seedling emergence of the weed community in no-till and tilled soybean, following a 2-year no-till sequence of oat and winter wheat. Statistical analysis indicated that weed density and time of emergence differed between no-till and tilled treatments at the 0.05 level of probability. The emergence curves were developed by cubic spline interpolation to show the emergence patterns for treatments averaged across years. Data points represented weekly means for soybean averaged across six replications in four site-years. (Adapted from Anderson[21].)

Corn–soybean sequence

We suggest growing corn first in this warm-season sequence because of high N levels in soil following alfalfa. Also, producers may be able to control weeds in corn without tillage. First, to suppress establishment and growth of cool-season weeds following tillage to control alfalfa, oat or spring triticales (× *Triticosecale*) could be planted in August. These crops will die over winter, but the remaining crop residue will favor the use of a stale seedbed in corn the next year to reduce early season weed emergence[16,17].

Second, implements have been developed to control weeds in corn without tillage. Donald[18] designed a between-row mower that controls weeds with two operations as effectively as herbicides in corn. Weeds in the row can be controlled by implements such as the finger weeder or rotary-tine weeder, if weed density is low and the crop is larger in size[2]. Density of warm-season weeds likely will be low after 3 years of alfalfa, whereas the stale seedbed will suppress early growth of weed seedlings present in corn.

Oat/pea–winter wheat sequence

A cool-season sequence of oat/pea mixture harvested for forage followed by winter wheat will suppress warm-season weeds during the 2-year interval. Weeds common in corn and soybean are not able to establish in winter wheat because of its competitive canopy. Some weed seedlings can establish in spring wheat or oat, but few weed seeds are produced. For example, green foxtail [*Setaria viridis* (L.) Beauv.] produces only 65 seeds/plant in spring wheat, whereas a plant growing in soybean can produce more than 1700 seeds[19]. The oat/pea mixture will further suppress establishment of warm-season weeds because pea supplements oat canopy development. An additional benefit of this sequence is that winter wheat yields 20% more following oat/pea compared with spring wheat or soybean as a preceding crop[20].

Soybean–corn sequence

We suggest planting soybean first in this sequence because N supply in the soil likely will be low after winter wheat, and would reduce yield of corn. Also, this sequence provides an opportunity for producers to replace tillage with a rye (*Secale cereale* L.) cover crop to control weeds in soybean. This suggestion is based on a recent study that quantified impact of an oat–winter wheat sequence on weed dynamics in soybean[21]. The study was established in a conventionally tilled field where the rotation had been corn–soybean, but oat and winter wheat were grown with no-till. After winter wheat harvest, treatments of no-till and tillage were established, with soybean planted the next growing season. Tillage consisted of chisel plowing in August and cultivating to prepare a seedbed in early May.

The number of weed seedlings emerging in no-till or tilled plots was determined weekly for the first 7 weeks of the growing season. Seedling density was fivefold higher after tillage compared with no-till (Fig. 5). Furthermore, seedling emergence was delayed in no-till; the initial germination flush was 2–3 weeks later. Consequently, soybean yield was not affected by weeds in no-till, whereas weeds reduced yield 25% in tilled soybean. Soybean tolerated weeds more in no-till because of lower density and delayed emergence of weeds.

Herbicides were used to control volunteer winter wheat after harvest in the no-till system, but other weeds were not present after harvesting oat or winter wheat because the

weed community consisted primarily of warm-season weeds due to the previous corn–soybean rotation. These weeds were not able to establish in oat or winter wheat.

Organic producers could gain this advantage with no-till by growing a rye cover crop between winter wheat and soybean to replace herbicides. Rye can be effectively controlled with mowing or a roller when plants are flowering, thus eliminating the need for tillage[22]. Rye normally flowers in early June, which results in soybean being planted late and yielding less. However, if rye is planted in mid-August after winter wheat harvest, flowering would occur in May[21]. Control with mowing or rolling at this time will avoid soybean yield loss due to late planting. Also, weeds that emerged in soybean could be controlled by between-row mowing[18] and within-row implements[2]. The low density and delayed emergence with no-till (Fig. 5) would increase the probability of effective weed management in soybean without tillage. This approach eliminates the need for tillage during the soybean season, and results in a 3-year interval of no-till with the oat/pea–winter wheat–soybean sequence. This 3-year interval of no-till will further help weed management by its impact on weed survival across time (Fig. 2).

We suggest establishing alfalfa with oat grown as a companion crop (Fig. 3). This practice will reduce the establishment of weeds in the first year of alfalfa.

Ancillary Benefits of This Rotational Framework

Additional options for weed management

Producers may be able to further suppress weed dynamics by using chaff collectors during harvesting of winter wheat and soybean to remove weed seeds from the field[23]. With some weeds, more than 70% of seeds produced can be collected during harvest. Effectiveness of other control tactics used by organic producers, such as steaming, flaming and cover crops, will improve with lower weed density[2,24,25]. Also, organic herbicides are being developed that may further reduce the need for tillage, such as controlling weeds present at planting time[3].

N management

Alfalfa will help organic producers with N management, as alfalfa can fix more than 100 kg N/ha by the second year of its establishment[26]. Peterson and Russelle[27] found that 3 years of alfalfa can supply more than 250 kg N/ha with biological fixation. Hoyt[28] showed that soil N produced by alfalfa was adequate for small grain production, even 4 years after alfalfa was eliminated by tillage. A further benefit of alfalfa is that its deep rooting patterns will access nitrates that may have leached downward in the soil profile and recycle this N for following crops[29].

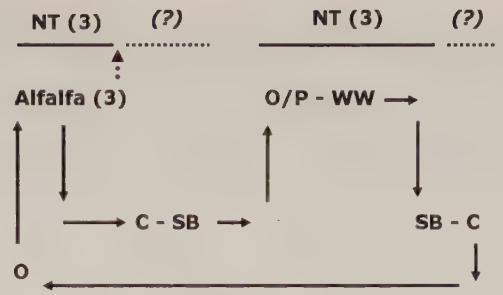

Figure 6. Possible 3-year intervals of no-till within the 9-year organic crop rotation. Abbreviations are: NT, no-till; C, corn; SB, soybean; O/P, oat–pea mixture for forage; WW, winter wheat; and O, oat (grown as a companion crop for establishing alfalfa). The (3) refers to 3 years of either alfalfa production or no-till. The question mark signifies that no-till may be possible with low weed density, whereas the dotted line with an arrow signifies tillage to convert alfalfa to cropland.

Yield benefit

This rotational framework should improve crop yield, as crops yield more when grown less frequently in a rotation[30]. For example, corn yielded 24% more when grown once every 4 years compared with once every 2 years[31]. Similarly, a 35-year rotation study in Wisconsin showed that corn yielded more in a rotation including 3 years of alfalfa compared with either continuous corn or a corn–soybean rotation[32]. This yield gain could not be accrued by adding additional fertilizer to the short rotations; the yield benefit of alfalfa was attributed to improved soil functioning.

Soil health

A concern with any cropping system that relies on tillage is its impact on soil health and structure[33]. Organic producers would like to reduce the intensity of tillage in their systems[34]. Our suggested rotation includes intervals of no-till, i.e., alfalfa and the oat/pea–winter wheat–soybean sequence, which may help producers repair the damage to soil accrued during years of intensive tillage (Fig. 6). An intriguing possibility is if weeds in corn can be controlled without tillage during the ninth year, a 7-year interval of no-till could occur before alfalfa is tilled in its third year. Long intervals of no-till will improve both weed management and soil health.

A recent study in the central Corn Belt evaluated the effect of alfalfa on soil health, as defined by nine bio-indicators[35]. Soil health improved when rotations include at least 3 years of perennial forages; in contrast, soil health declined with continuous corn or corn–soybean rotations. All rotations included tillage to prepare seedbeds for crops.

Summary

Our goal with this paper was to provide a conceptual framework to help organic producers design rotations to

reduce weed density in their croplands. With fewer weeds, cultural tactics to control weeds in crops will be more effective. Also, this approach may provide other opportunities for weed management, such as that shown in Figure 5, where a sequence of small grains followed by soybean may be grown without tillage. This rotation has not been field tested, but we believe organic producers can reduce weed density by designing rotations to include crops with a diversity of life cycles and planting dates, perennial forages and intervals of no-till. In addition, this rotational approach will likely accrue a multitude of other benefits in addition to improved weed management.

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Energy efficiency of organic pear production in greenhouses in China

Yuexian Liu[1,2*], Henning Høgh-Jensen[3], Henrik Egelyng[4], and Vibeke Langer[1]

[1]Department of Agriculture and Ecology, Faculty of Life Sciences, University of Copenhagen, Højbakkegaard Alle 9, DK-2630 Taastrup, Denmark.
[2]Information Institute, Beijing Academy of Agriculture and Forestry, Beijing 100094, P.R. China.
[3]Department of Policy Analysis, National Environmental Research Institute, Aarhus University, Frederiksborgvej 399, DK-4000 Roskilde, Denmark.
[4]Danish Institute for International Studies, Strandgade 56, DK-1401 Copenhagen, Denmark.
*Corresponding author: liy@life.ku.dk

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Abstract

The development of organic protected cultivation taking place in densely populated areas has raised the question whether it is an environmentally friendly production system. The present study investigated energy consumption of organic pear production in two production systems, namely in traditional Chinese solar greenhouses and in the open field. In both production systems, energy output/input ratio and energy productivity were used as indicators to determine the energy efficiency; yield, cost of production, net economic return per land area unit and benefit/cost ratio were used to evaluate economic productivity. The analysis results indicated that energy input and energy output per land area unit in the solar greenhouse were higher than in the open field; whereas energy efficiency in terms of output/input ratio and energy productivity were lower in the solar greenhouse than those in the open field. However, if energy input sequestered in the protected structure was excluded in the solar greenhouse production system, energy efficiency was higher in the greenhouse system than in the open-field system. Our analysis further showed that the economic costs, the yield, cost of production, gross product value and net income per land area unit in the greenhouse were more than twice as high as those in the open field due to a higher tree density and a premium price. However, the production taking place in the open field used a great share of renewable energy and higher energy efficiency, which may comply more with the principles of organic farming than the greenhouse production system.

Key words: organic pear, energy efficiency, economic analysis, greenhouse

Introduction

A substantial greenhouse industry has emerged near Chinese cities concentrating on high-value products like certified organic fruits for domestic consumption. In 2004, the total area of protected cultivation in China was 2.5 million ha accounting for 1.6% of the total arable land area[1]. About 50% of the protected cultivation area is occupied by traditional Chinese solar greenhouses[2]. This development of organic protected cultivation is driven by several factors: the shortage of land in the densely populated peri-urban areas and a growing market for fresh organic produce. The solar greenhouses offer an opportunity for extending the season, providing the farmers with the benefit of early harvests and good premium prices. However, little attention has been given to the energy costs in this type of organic protected cultivation and its compliance with the expectations of organic production systems of environmental soundness.

Efficient use of energy is an important parameter in the evaluation of the environmental impact of production systems. Previous studies on energy consumption in protected cultivation by Fluck and Shaw[3], Stanhill[4], Biondi et al.[5] and El-Helepi[6] indicated an increase of energy input with an improved productivity as a result of intensive inputs of protected structures. Comparing open field and various protected tomato production systems, Stanhill[4] reported that the indirect energy sequestered in the protective structures accounted for more than 50% of the total energy inputs in an unheated glasshouse system. However, he did

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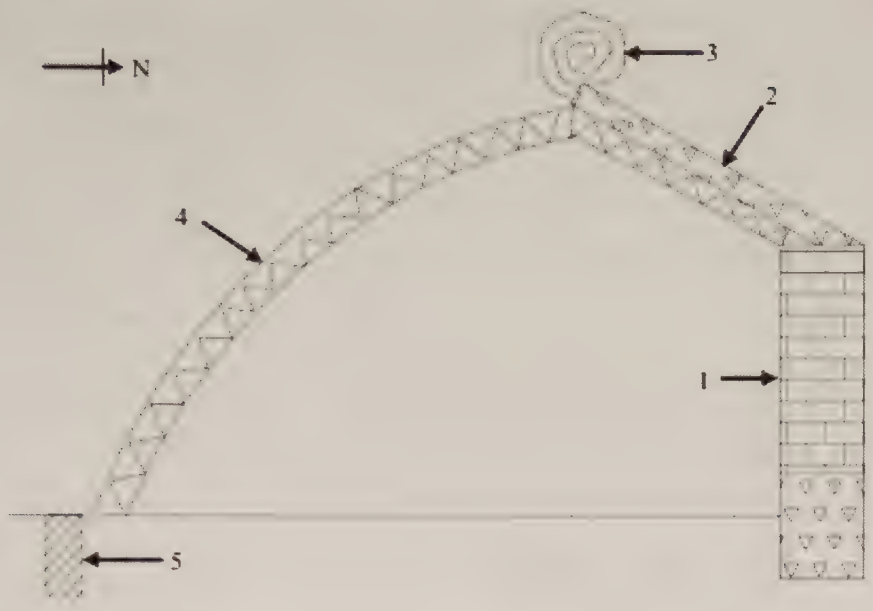

Figure 1. Structure of the traditional Chinese solar greenhouse: 1, concrete north wall; 2, the back roof; 3, the heat insulation mattress; 4, the frame of the front roof; 5, the ditch for preventing greenhouse heat loss through horizontal soil heat conduction.

find the energy intensity of the studied unheated glasshouse system to be of the same magnitude as plastic covers and tunnels, whereas the intensity in heated glasshouses was 30 times higher. This suggests that systems like the traditional Chinese solar greenhouse, exploiting natural advantages like high winter solar radiation, may have potential as an environmentally sound production system in areas with a scarcity of land.

Farmers, however, are interested in profitability rather than in energy efficiency, especially in regions with limited agricultural land. Economic benefit per area is the major driving force for the protected cultivation. Therefore, a combination of economy and energy analysis of a production system is appropriate for the application of best practice strategies for sustainable development[7].

In this study, energy efficiency, energy intensity and the amounts of renewable energy use, as well as net returns per land area unit and the benefit/cost ratio, were compared between organic pears produced in an open field and in a traditional solar greenhouse, with the aim of identifying possible strategies for reducing energy consumption in protected organic cultivation.

Materials and methods

Description of the two organic pear production systems

The study was conducted in two organic pear production systems in Beijing suburbs, China during 2007–2008. The traditional Chinese solar greenhouse used for the organic pear production is located in the east of Beijing (40°17′N, 117°16′E), Pinggu District, and the open field is located in the southeast of Beijing (39°60′N, 116°49′E), Daxing District. The traditional Chinese solar greenhouse is the so-called 'energy-saving greenhouse'[8], shown in Figure 1. The greenhouse consists of a concrete non-transparent wall and gables on the north, west and east sides, respectively, and a transparent plastic incline roof on the south side[2]. Energy for heating stems from solar radiation, as insulation mattress are rolled up during the daytime, and put down from late afternoon to early morning to prevent heat loss. The north wall stores solar energy by absorbing solar radiation during the daytime and the thermal radiation from the wall maintains the temperature in the greenhouse during night. The pear variety produced is *Pyrus pyrifolia (Burm. f.)* Nakai, called Whangkeum Bae. In the greenhouse, pears were harvested at the beginning of June, while in the open-field pears were harvested in the middle of August.

The open-field system represents a common organic production system in the Daxing District, covering *c.* 300 ha of land in 2007. The system of organic pears produced in the greenhouse is seen more occasionally (approx. 3 ha in the district), but the solar greenhouse is widespread. Tree density in the greenhouse production system is almost twice as high as in the open-field system (990 and 405 trees ha^{-1}, respectively).

Data collection

The open-field farm is owned by an association and the data were collected through personal interviews with the production manager. The data in the greenhouse farm were collected through personal interviews with the grower.

The boundary of the energy analysis was the field gate, and marketing, sorting and storage of the products were not

Table 1. Field operations in organic pear production systems in the Beijing area.

	Frequency and comments	
Field operations	**Open field**	**Solar greenhouse**
Climate management	Without protective structure	With protective structure
Irrigation	5 times per year based on water availability after March	4 times per year in the period of January to April
Pollination	Artificial pollination in the middle of April	Mainly by bee pollination and subsidiary artificial pollination in the end of January
Fruit thinning	Fruit thinning by scissors in the end of April	Fruit thinning by hand in the period of January to February
Bag covering	Bag covering with one big and one small paper bag at the beginning of May	Bag covering with only one bag at the beginning of March
Summer pruning	Pruning by special scissors in the period of May to June	Pruning by special scissors in June
Winter pruning	Pruning by special scissors in January to February	
Branch binding	Branch binding and pulling before March	Branch binding and pulling in January
Fertilizer application	Poultry manure applied every year at the end of October	Sheep manure and organic compost applied in September and October
Pest management	Organic pesticides sprayed in the growing season	Organic pesticides sprayed in the growing season
Weed control	By mower in the growing season	By black polyethylene mulch in the growing season
Soil cultivation	With rotary tiller at the end of October	No soil cultivation
Harvesting	Hand picking in the middle of August	Hand picking at the beginning of June

included. For example, transport from the production sites to final users in both systems was assumed to be the same, therefore, the difference of transportation costs in terms of energy and economic costs were not considered in the analysis. For both production systems, energy, material and fuel consumption, as well as time needed to complete field operations, were recorded. Information on labor hours, tools (pruning scissors and hoe, etc.), machinery, energy consumption, uses of farmyard manure and organic pesticides was collected. Field operations in the greenhouse and in the open-field system during the study period (2007–2008) are shown in Table 1. In both organic pear production systems, farmyard manure and organic compost were used as organic fertilizers.

Energy accounting

The energy analysis conducted in this study was aimed at estimating the difference in total energy inputs between organic pears produced in the open field and in the greenhouse. Input categories were machinery, labor, fossil fuel, organic fertilizers, organic pesticides, mulch input and protective structure of the traditional Chinese solar greenhouse, as described by some other researchers[3,4,6].

The following applications were identified to be the possible sources of additional energy use in the greenhouse system: (1) heat insulation mattress, including agricultural polyethylene film and straw mulch; and (2) the amortization of the solar greenhouse. The energy sequestered in the amortization of the solar greenhouse was included and calculated in 20-year depreciation, whereas the energy on machinery and labor for the construction of the solar greenhouse was excluded in this study.

In addition, input energy in this study was categorized into two groups: fossil energy and renewable energy. Fossil energy included direct energy (electricity, gasoline and diesel fuel) and indirect energy (machinery, bags, mulch input and protective structure of the solar greenhouse). Renewable energy included labor, organic fertilizers and organic pesticides.

For the energy output side in the two organic production systems, we considered only biological energy that is embodied in cash crops, i.e. organic pears.

Energy equivalents calculation

The energy equivalents of inputs used in the two organic pear production systems are listed in Tables 2–4. The embodied energy of machinery and human labor was determined. Total energy embodied in machinery included energy for raw materials, manufacturing, repairs and maintenance, and energy for transportation (Table 3). Taking into account the total weight and the life of machinery as used in practice, the energy required for each operation was calculated.

Energy equivalents for biological pesticides were not recorded in the literature. However, these are permitted and used for pest management on certified organic production

Table 2. Energy equivalents of inputs of consumables and human labor and outputs.

Item	Unit	Energy equivalents (MJ unit^{-1})	Life (years)	References
Human labor	h	1.58		9
Plastics rope	kg	96.4	1	10
Fertilizer	kg			11
Nitrogen		50		
Phosphorus		11.85		
Potassium		4.22		
Pesticides	kg			12
Insecticide		237		
Fungicide		196		
Diesel fuel	l	47.79		13
Gasoline	l	42.33		13
Electricity	kWh	12.5		11
Black polyethylene mulch	kg	158	1	10
Paper bag	kg	46.6		14
Pollen	kg	0.15		15
Pear	kg	2.09		15

in China. Therefore, we estimated the energy equivalent of biological pesticides based on the active ingredient, as for chemical pesticides.

Depending on the context, manure may be considered either a valuable source of nutrients replacing synthetic fertilizers, a waste product from livestock production, or a potential energy source, e.g. for biogas production. In this study, we regarded manure as a source of nutrients, and the 'substitution method' was used to calculate the energy input of animal manure, which equates the energy equivalent of farmyard manure with that of mineral fertilizer equivalents corresponding to the fertilization effect of the applied manure[16,22,23,24]. Since nitrogen availability of organic manure is lower than that of mineral fertilizer, 1 kg of N in organic fertilizer is assumed to substitute 0.428 kg mineral fertilizer N[23]. The effectiveness of organic fertilizer P and K was assumed to be similar to that of mineral P and K for the sake of simplicity[25]. The energy content of farmyard manure used as fertilizer was calculated by multiplying available N, P and K contents with the energy required to produce the corresponding amount of synthetic N, P and K fertilizers, respectively.

Calculation of energy balancing indicators and economic indicators

In this study, energy balancing indicators such as output–input ratio (energy efficiency), energy productivity and energy intensity for organic pear production were calculated using the following equations (1)–(3); economic indicators such as net income and benefit–cost ratio were calculated using the equations (4) and (5):

$$\text{Output–input ratio} = \frac{\text{Energy output (MJ/ha)}}{\text{Energy input (MJ/ha)}} \quad (1)$$

$$\text{Energy productivity} = \frac{\text{Energy output (MJ/ha)}}{\text{Pear output (kg/ha)}} \quad (2)$$

$$\text{Energy intensity} = \frac{\text{Energy input (MJ/ha)}}{\text{Pear output (kg/ha)}} \quad (3)$$

$$\text{Net income} = \text{Gross product value (\$/ha)} - \text{Cost of production (\$/ha)} \quad (4)$$

$$\text{Benefit–cost ratio} = \frac{\text{Gross product value (\$/ha)}}{\text{Cost of production (\$/ha)}} \quad (5)$$

Results and discussion

Distribution of energy inputs for field operations between two production systems

Energy inputs for field operations per land area unit for organic pear production in the open field and in the solar greenhouse are summarized in Table 5. Overall, organic pears produced in the greenhouse were more than ten times as energy demanding as in the open field. This was mainly due to the large energy cost of the protective structure including the amortization of the greenhouse and heat insulation mattress, which accounted for 84% of the total energy use in the solar greenhouse.

Energy inputs for field operations were twice as high in the greenhouse (143 GJ ha^{-1}) as in the open field (76 GJ ha^{-1}), if the energy cost of the protective structure was excluded. In the open-field system, energy input for fertilizer application was the largest contributor to the energy consumption (74%). Producing organic pears in the solar greenhouse required additional energy for field operations such as pest management, weed control and irrigation compared with organic pears produced in the open field, whereas energy input on soil cultivation was lower in the greenhouse[3,6].

Energy input for irrigation in the greenhouse, where trees largely depended on irrigation and the water requirement per land area unit was greater due to the higher tree density, was more than five times that of the open field. Fluck and Shaw[3] and Stanhill[4] also reported more energy to be required for irrigation in protected cultivation, including both direct energy for irrigation and indirect energy for irrigation systems. Also, the energy inputs for pest management in the open-field system were 50% less than those in the greenhouse system. Among these, energy input for organic pesticides was 2.6 GJ ha^{-1} in the open field, which was 71% less than that in the greenhouse since humidity and temperature were more favorable in the greenhouse for pest infestation. Stanhill[4] also reported that 33–44% more energy on pesticides was consumed in an unheated glasshouse than in the open field. However, El-Helepi[6]

Table 3. Energy equivalents of machinery and hardware used in the study.

Item	Unit	Energy equivalents (MJ unit^{-1})	Mass (kg)	Life (years)	References
Machinery	kg	210			9
Sprayer			6.5	5	
Mower			5.6	3	
Rotary tiller			31	5	
Agricultural tractor			1100	12	
Wire	kg			5	
Tools (scissors, hoe, etc.)	h	0.1			15 (adapted)
Irrigation system	m^3 m	4.95			11
Transportation	kg km	0.005			16

Table 4. Energy equivalents of inputs for the traditional Chinese solar greenhouse. (The construction of the solar greenhouse was sourced from the GB/T 19561–2004. 'Rules for constructing the energy saving sunlight greenhouse in cold zones', issued by the General Administration of Quality Supervision, Inspection and Quarantine (AQSIQ) and Standardization Administration of the People's Republic of China in 2004.).

Item	Unit	Energy equivalents (MJ unit^{-1})	Life (years)	References
Agricultural polyethylene mulch	kg	158	2	10
Straw mulch	kg	0.84	4	17
Greenhouse construction			20	
Brick	Each	1.3×10^3		18
Natural aggregates	tonne	30		19
Cement	tonne	4.2×10^3		20
Quick lime	tonne	7.25×10^3		21
Asphalt-saturated felts	pound	14.3		21
Asphalt	tonne	16.07×10^3		21
Carbon steel	tonne	27.5×10^3		20

found that the protected cultivation system consumed less energy in terms of pesticides compared to the open-field system, due to a reduction in the number of treatments. The energy input for weed control in the greenhouse was much more than in the open field. In the greenhouse, the black polyethylene mulch used for weed control resulted in a large energy cost (33 GJ ha^{-1}), which accounted for 98% of the energy inputs for weed control; whereas the energy input of the mower, and correspondingly direct energy accounted for weed control in the open field, only amounted to 0.6 GJ ha^{-1}.

Energy inputs on soil cultivation in the open-field system were 1.5 GJ ha^{-1}, while there were no energy inputs for soil cultivation in the greenhouse system. This is in accordance with the results by Fluck and Shaw[3] and El-Helepi[6] reported that energy consumption could be decreased with plastic mulch for fewer cultivations and fewer applications of herbicides.

The energy inputs on machinery in the open field (29 GJ ha^{-1}) were slightly higher than that in the greenhouse (27 GJ ha^{-1}). This can be explained by the fact that the greenhouse system involves less use of large machinery such as agricultural tractors and rotary tiller. Consequently, the energy expenditure for fuel in the open-field system (4.5 GJ ha^{-1}) was 49% more than that for the greenhouse

Table 5. Energy inputs (GJ ha^{-1}) for field operations in the open field and in the greenhouse systems.

Field operations	Open field	Greenhouse
Protective structure	0	760
Irrigation	4.90	27.2
Pollination	0.03	1.01
Fruit thinning	0.76	1.42
Bag covering	3.78	14.6
Branch binding	1.63	0.65
Summer pruning	0.26	0.50
Winter pruning	0.34	0.75
Pest management	6.00	12.0
Fertilization application	55.8	48.8
Weed control	0.65	34.4
Soil cultivation	1.52	0
Harvesting	0.12	1.66
Total	76	903

Table 6. Total energy input (GJ ha^{-1}) in the form of fossil and renewable energy in organic pear production in the open field and greenhouse systems.

Farming types	Total energy input	Fossil energy		Renewable energy
		Direct energy	Indirect energy	
Open field	76	4 (6%)	36 (47%)	36 (47%)
Greenhouse	903	3 (0.3%)	830 (92%)	70 (7.7%)

Table 7. Energy balance indicators for organic pear production in the open field and in the greenhouse.

Items	Open field	Greenhouse
Energy input (GJ ha^{-1})	76	903
Energy output (GJ ha^{-1})	35	78
Energy output/input ratio	0.46	0.09
Energy productivity(kg GJ^{-1})	218	42
Energy intensity (MJ kg^{-1})	5	24

system (3 GJ ha^{-1}). The machinery in the open-field system was mainly used for field operations, such as soil cultivation, weed control and pest management.

Fossil and renewable energy

The total energy input classified as fossil energy and renewable energy is illustrated in Table 6. The share of fossil energy input including direct and indirect energy was significantly higher in the greenhouse system (833 GJ ha^{-1}) than in the open-field system (40 GJ ha^{-1}) as a result of larger energy consumption on protective structures in the greenhouse, which accounts for 84%. Renewable energy input in the open-field system accounted for 47% of the total energy input, but 7.7% in the greenhouse system. Organic fertilizer as renewable energy resource had the highest share in the open-field systems (38%).

Assessment of energy efficiency by using different energy balance indicators in the two production systems

Energy balance indicators for organic pear production in the open field and in the solar greenhouse are summarized in Table 7. Energy input per land area unit was much higher in the greenhouse production system compared with the open-field system, while energy output in the greenhouse production system (78 GJ ha^{-1}) was twice as high as that of the open field (35 GJ ha^{-1}). When comparing the two production systems with regard to energy efficiency, lower output/input ratio was found in the greenhouse (Table 7), whereas energy intensity in the greenhouse system was higher compared with the open-field system. Similar results have been reported by some earlier studies[3–6]—that protected cultivation systems had lower energy efficiency and higher energy intensity when compared with the open-field system. This is because, in the protected cultivation

Table 8. Economic results (per land area unit and per 100 trees) for organic pears produced in the open field and in the greenhouse (excluding the economic expense for the construction of the solar greenhouse).

Item	Open field	Greenhouse
Yield (kg ha^{-1})	16,608	37,506
Cost of production ($ ha^{-1})	9078	23,558
Gross product value ($ ha^{-1})	35,828	87,299
Net incomes ($ ha^{-1})	26,751	63,740
Cost of production ($ per 100 trees)	2241	2387
Gross product value ($ per 100 trees)	8846	8847
Net incomes ($ per 100 trees)	6605	6459
Benefit/cost ratio	3.94	3.70

Note: US $1 equals ¥ 6.85. (December 2008).

systems, the energy sequestered in the protective structure and fossil fuel represented a significant fraction of the total energy requirement as the degree of environmental control increased. In the present study, the fossil energy and energy sequestered in the protective structure accounted for 83% of the total energy inputs in the solar greenhouse system. This is in agreement with the results given by Stanhill[4] that a large fraction of the total energy inputs were the energy sequestered in the protective structure and fossil fuel for the unheated glasshouse in tomato production.

However, if we only consider field operations excluding the energy sequestered in the protective structure, the solar greenhouse system used slightly less energy per unit of product (3.8 MJ kg^{-1}) than the open-field system (4.6 MJ kg^{-1}). Nevertheless, the total energy inputs were still higher in the solar greenhouse, approximately twice higher than in the open-field system, which was in accordance with the findings reported by Ozkan et al.[26] that conventional grape production in the greenhouse had higher energy inputs but lower energy efficiency than that in the open field, even excluding the energy sequestered in the protective structure.

Comparing economic benefits between the two production systems

Within the range of production systems examined by Fluck and Shaw[3], Stanhill[4], Biondi et al.[5] and El-Helepi[6] and in the present study, the main driving forces for higher energy inputs associated with protected cultivation were to increase crop yield, to produce out-of-season crops and to

obtain more economic benefits, especially in contexts where arable land is limited. In this context, yield, production costs, gross product values, net economic return per land area unit and benefit/cost ratio are crucial factors to be considered. As shown in Table 8, the yield, cost of production, gross product value and net income per land area unit in the greenhouse were doubled in relation to those in the open field. However, the benefit–cost ratio in the open-field system (3.94) was slightly higher than that in the greenhouse system (3.70). A similar result has been found by Ozkan et al.[26]—that the benefit/cost ratio was lower in greenhouse grape production compared to the open-field system, while energy efficiency in the greenhouse system was lower than that in the open field.

However, if the calculation was based on 100 trees, the greenhouse system had lower yield, less net income and much more production cost. The yield and net income per 100 trees in the greenhouse system were 7.3 and 2.21%, respectively, less than in the open field, whereas the gross product values per 100 trees of both organic pear production systems were similar. This was, however, ascribed to 15% higher sale prices of the pears produced in the greenhouse system due to harvesting 2–3 months earlier than those in the open field. It can be concluded that the higher tree density in the greenhouse was some kind of strategy to increase yields and obtain higher net income in places where arable land is limited.

Strategies to reduce energy inputs for organic pear production in the greenhouse

Since the protective structure represents by far the largest energy cost in the solar greenhouse system, any potential reduction in the energy inputs for this component would improve the system. Prolonging the life span of the structure, reducing polyethylene thickness[3] or reusing plastic for mulching[27] would all result in a reduced total energy input and increased energy efficiency in the greenhouse production system. For instance, if the life span of the solar greenhouse could be prolonged from 20 to 30 years, 25% of the energy sequestered in the construction of the solar greenhouse would be saved. In addition, as suggested by Munoz et al.[28], attention should be given to the use of recycled material in building the protective structures. Also, reusing the black polyethylene mulch to control weeds in the greenhouse system would reduce the energy input by 33 GJ ha^{-1}.

Conclusions

Energy consumption per land area unit and per unit of product are fundamental indicators to assess the environmental impact of crop production. The current findings indicate that due to the high energy cost of protective structures, both energy efficiency in terms of output/input ratio and energy productivity are higher in an open-field pear system than in a solar greenhouse, resulting in more energy intensive production in the greenhouse system. Among the inputs, the protective structure accounts for the main part of the energy demands in the greenhouse production system, while organic fertilizer application uses most energy in the open-field system. Including all components of the system, the open-field system may be more in compliance with the expectations of environmental soundness in organic farming than the solar greenhouse. However, given the higher net income per land area unit in the organic greenhouse production system, the traditional Chinese solar greenhouse may have potential to be developed into a viable organic production system. This will require successful development of less energy costly protective structures through increased use of recycled materials and improved durability.

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The effect of biogas digestion on the environmental impact and energy balances in organic cropping systems using the life-cycle assessment methodology

Jens Michel[1], Achim Weiske[1] and Kurt Möller[2,*]

[1]Deutsches Biomasse-Forschungs-Zentrum, Torgauer Strasse 116, 04347 Leipzig, Germany.
[2]Department of Plant Nutrition, Universität Hohenheim, D-70593 Stuttgart, Germany.
*Corresponding author: kurt.moeller@alumni.tum.de

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Abstract

A life-cycle assessment (LCA) was carried out to compare the environmental performance of different organic cropping systems with and without digestion of slurry and crop residues. The aims of the present study are: (1) to compare the environmental performance of organic farming dairy systems with the currently prevalent animal housing systems [solid farmyard manure (FYM) versus liquid slurry] as the main reference systems; (2) to analyze the effect of the implementation of a biogas digestion system on the consumption of fossil fuels and production of electrical energy; (3) to quantify the effects of the implementation of a biogas digestion system on the environment; and (4) to compare the obtained net energy yields with other means of obtaining energy by using the farmland area. The considered impact categories are greenhouse gas (GHG) balances, acidification, eutrophication and groundwater pollution. LCA results indicated that total emissions in systems based on FYM are much higher than in liquid slurry systems for most of the considered impact categories. The benefits of digestion of stable wastes in comparison with the reference system without digestion are mainly (1) the net reduction of the emissions of GHG and (2) energy recovery from produced biogas, while the disadvantages can be higher emissions of NH_3 after spreading. The effects of additional biogas digestion of biomass such as crop residues (e.g., straw of peas and cereals) and cover crops are: (1) an optimization of the N-cycle and therewith higher yields; (2) higher energy production per unit arable land; (3) a further reduction of the GHG balance; but (4) higher N-related environmental burdens like eutrophication and acidification. The offsets of fossil fuel emissions were the largest GHG sink in most of the biogas digestion systems. The inclusion of a biogas plant into organic cropping systems and the use of the available wastes for production of energy largely increased the overall productivity of the farming system and matched very well the basic principles of organic farming such as a high self-sufficiency of the cropping system and reducing as much as possible the environmental impact of farming.

Key words: biogas digestion, life-cycle assessment, organic farming, acidification, eutrophication, global warming potential, groundwater pollution

Introduction

The direct emissions of CO_2, CH_4 and N_2O from agriculture account for approximately one-fifth of the annual increase in radiative forcing leading to climate change[1]. This proportion is even higher if indirect emissions due to the energy use by agriculture in fertilizers, machinery, etc. are included in the estimates[2]. Agriculture accounts for approximately 50% of the anthropogenic CH_4 emissions[3]. Emissions from farms with a stock of ruminant animals are particularly high. Agriculture also accounts for 80% of the global anthropogenic N_2O emissions and about 40% of these originate from manure management[4]. In addition, soils are also important sources for N_2O emissions[5]. Furthermore, volatilization of NH_3 from animal wastes can occur after application to soil, during housing and storage, or grazing[6]. The volatilized NH_3 is deposited partly locally and partly transported long distances from the source before being deposited[7]. Deposited NH_3 causes eutrophication of N-limited aquatic and terrestrial ecosystems and

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contributes to the increased acidification of sensitive ecosystems[8].

Concern about energy self-sufficiency and global warming in recent decades has stimulated interest in using biomass for energy production. Biogas digesters are able to produce energy from dedicated energy crops like silage maize and cereal grains, as well as from organic residues like stable wastes, crop residues, etc. The emergence of commercial-scale technologies for producing methane from wastes and dedicated energy crops is expected to create important economic opportunities for farmers, while reducing fossil fuel dependence[9,10], GHG emissions[11,12], nitrate leaching risk[12] and enhancing crop productivity by using digested effluents (= digestate) as manures[13,14]. Biogas digestion encompasses the aim of minimizing emissions of odors, NH_3, N_2O and CH_4 during storage of manure, if the effluents are stored in enclosed tanks after digestion[15,16]. Therefore, biogas production by anaerobic digestion is a promising means of achieving multiple environmental benefits such as substitution of fossil fuels, reduction of nitrate leaching and GHG emissions. The use of digested materials on farmland can improve the nutrient use efficiency[17].

The implementation and operation of a biogas digester are related to additional inputs and environmental burdens, e.g., for handling the substrates and returning the effluents, as manure, to the fields, for construction and dismantling the digester, etc. The big differences among diverse biogas systems make them complex to study from an environmental point of view; the environmental impact of each system is more or less unique[18]. Furthermore, the total environmental impact of the implementation of a biogas digestion system depends mainly on the reference system replaced, concerning energy consumption, animal waste handling and farming system. There is a lack of broad environmental systems analyses, which include the entire biogas fuel-chain, and the indirect environmental impact of replacing different reference systems[18].

The life-cycle assessment (LCA) methodology is a holistic tool used to assess the environmental impacts of a system or product from 'cradle to grave'. It was designed to study all environmental impacts[19]. The present paper relates the studies presented by Stinner et al.[13] and Möller et al.[14] in order to aggregate the fossil fuel consumption and the environmental impact of various biogas systems and the replacement of different reference systems common in organic farming. The aims of the present study are: (1) to compare the environmental performance of organic farming dairy systems with the currently prevalent animal housing systems [solid farmyard manure (FYM) versus liquid slurry] as the main reference systems; (2) to analyze the effect of the implementation of a biogas digestion system on the consumption of fossil fuels and production of electrical energy; (3) to quantify the effects of the implementation of a biogas digestion system on the environment; and (4) to compare the obtained net energy yields with other means of obtaining energy by using the farmland area. The chosen environmental impact categories are the greenhouse gas (GHG) balances, the acidification potential, the eutrophication potential and the potential groundwater pollution, which represent the most important impacts connected with agricultural activities.

Materials and Methods

LCA

To analyze the environmental impact of different manuring systems and of biogas digestion in organic farming systems, an LCA was carried out. The LCA method is internationally standardized. According to ISO 14040 ff, LCA is divided into four steps: (1) goal and scope definition; (2) life-cycle inventory (LCI) analysis; (3) life-cycle impact assessment (LCIA); and (d) interpretation[20–23]. To carry out a full LCA, it is usual to use a number of impact categories ranging from energy consumption to acidification.

System boundaries and delimitations

The present analysis deals with the entire life-cycle flow of the described cropping systems, including crop production, animal husbandry and power generation. In the case of biogas combustion, electricity is generated from the produced gas. The time frame is the milk, crop and electrical energy production over 1 year and follows the results obtained in field experiments in the time period 2002–2005[13,14].

Description of the systems

The present publication is based on studies published by Stinner et al.[13] and Möller et al.[14]. The reference cropping systems studied were designed according to the most common systems in organic farming practice in Germany, representing best management practices. Five cropping systems (two reference systems and three biogas systems), simultaneously representing five different manuring treatments, were implemented in trial series I, representing a mixed organic farming system with dairy husbandry at 0.8 livestock units ha^{-1} held loose in cubicles (Table 1). The designed arable crop rotation in trial series I included: year 1–2, clover/grass-ley (2 years); year 3, winter wheat (*Triticum aestivum*)+cover crops; year 4, potatoes (*Solanum tuberosum*) on 20% of the field and silage maize (*Zea mays*) on 80% of the field; year 5, winter rye (*Secale cereale*)+cover crops; year 6, spring peas (*Pisum sativum*)+cover crops; year 7, spelt (*T. aestivum* ssp. *spelta*)+cover crops; year 8, spring wheat (*T. aestivum*) with undersown clover/grass-ley. The following five manuring treatments were implemented in trial series I (in parentheses: used abbreviations).

FYM. Wastes from stables (urine and feces) with high additions of straw from animal bedding results in FYM. The straw for animal bedding was harvested from all

Table 1. Description of cropping systems assessed in the present study.

Cropping system	Abbrev.	Stable wastes	Management of crop residues and cover crops
Trial series I			
Solid farmyard manure	FYM	Straw-based FYM, stored in covered boxes	Cereal straw was harvested, the cover crops were incorporated on field
Liquid undigested slurry	US	Liquid slurry, not digested, stored in closed boxes	Wheat straw was harvested, the straw of the other crops as well as the cover crops biomass were incorporated on field
Liquid digested slurry	DS		
Digestion of slurry and field residues	DS+FR	Liquid slurry, digested, after digestion stored in closed boxes	The straw of all crops as well as the cover crops was harvested, digested, and after digestion reallocated as manure within crop rotation
Digestion of slurry, field residues and external substrates at 40 kg N ha^{-1}	DS+FER		
Trial series II			
Usual stockless management without livestock	wL	Not available	Remained on field (ploughed in and mulched), inclusive of clover/grass-ley and cover crops
Stockless management with digestion of field residues	wL-FR	Not available	Harvested (including clover/grass-ley), digested, effluents reallocated as manure within crop rotation
Stockless management with digestion of field residues and external substrates at 40 kg N ha^{-1}	wL-FER	Not available	Harvested (including clover/grass-ley), digested, effluents reallocated as manure within crop rotation

Abbrev., abbreviation.

cereal crops. Cover crop biomass was mulched and ploughed in.

Undigested liquid slurry (US). Liquid cattle slurry. Bedding consisted of a mixture of daily use of 0.6 kg straw and 2 kg of lime (DM content: 94%; $CaCO_3$: 60%; $MgCO_3$: 25%). Straw of winter and spring wheat was removed (harvested) for animal bedding in the stable. The remaining crop residues and the cover crops were mulched and ploughed in.

Digested liquid slurry (DS). Liquid cattle slurry that was digested. After digestion effluents were stored in closed boxes. The animal bedding and the management of crop residues and cover crops matches the description of the US treatment.

Digestion of liquid slurry and field residues (DS+FR). Liquid cattle slurry was collected and digested as described in the DS system. Straw not needed for animal bedding (straw of peas, rye and spelt) and the cover crop biomass were also harvested for digestion, in comparison with, e.g., DS, where the residues not needed for animal bedding were left on the field and incorporated directly. The effluents of the digester were reallocated mainly in spring within the same crop rotation as manures for the nonlegume crops.

Digestion of liquid slurry, field residues and external substrates (DS+FER). As in DS+FR, stable wastes and crop residues were collected, digested and reallocated within the same crop rotation. Off-farm purchased substrates (silage maize) were digested in amounts according to EC guidelines for organic farming, resulting in an additional N input (40 kg N ha^{-1} yr^{-1}). The effluents of the digester were reallocated mainly in spring within the same crop rotation as manures for the nonlegume crops.

Trial series II represented a crop rotation for a stockless organic farming system, with three manuring treatments implemented (Table 1). The cropping system consisted of a six-field crop rotation, which included six crops: year 1, clover/grass-ley; year 2, potatoes; year 3, winter wheat+cover crops; year 4, spring peas+cover crops; year 5, winter wheat+cover crops; year 6, spring wheat with undersown clover/grass-ley. The implemented treatments were as follows (in parentheses: used abbreviations).

Stockless system without livestock with the common mulching practice (wL). The plant biomass of the clover/grass-ley, cover crops and the crop residues remained on the field, evenly spread over the surface and ploughed into the soil. No mobile manure was available. The clover/grass-ley was cut with a mulching machine, which chops the plant material into small pieces.

Stockless system without livestock with digestion of field residues (wL-FR). The clover/grass-ley, cover crops and crop residues (straw of wheat and pea crops) were harvested, removed and digested. The effluents of the digester were reallocated mainly in spring within the same crop rotation as manures for the nonlegume crops.

Stockless system without livestock with digestion of field residues and external substrates (wL-FER). The clover/grass-ley, cover crops and crop residues were harvested, removed and digested, as described for wL-FR. External substrates (silage maize) were digested in amounts according to EC guidelines for organic farming, resulting in an additional N input (40 kg N ha^{-1} yr^{-1}). The effluents of the digester were reallocated mainly in

Table 2. Inventory of the agricultural operations in the field and frequency of operations.

	Winter wheat	Spring wheat	Winter rye	Spelt	Silage maize	Potatoes	Spring peas	Clover/ grass-ley 1	Clover/ grass-ley 2	Permanent grassland	Cover cropping
Ploughing	1	1	1	1	1	1	1	1	–	–	–
Grubbing/cultivating	–	–	–	–	–	–	–	1	–	–	1
Mulching	–	–	–	–	–	–	–	4[1]	–	–	1[2]
Sowing	1	1	1	1	1	–	1	1	–	–	1
Potato planting	–	–	–	–	–	1	–	–	–	–	–
Spreading liquid and solid organic manures	1	1	1	1	2	2	–	–	–	2	–
Curry-comb	3	2	2	2	1	–	1	–	–	–	–
Hoeing	–	–	–	–	2	2	–	–	–	–	–
Pesticide application	–	–	–	–	–	1	–	–	–	–	–
Combine harvesting	1	1	1	1	–	–	1	–	–	–	–
Towing/leveling in late winter	–	–	–	–	–	–	–	1	1	1	–
Mowing	–	–	–	–	–	–	–	4	3	4	1[3]
Tedding	–	–	–	–	–	–	–	4	3	4	1[3]
Swathing	–	–	–	–	–	–	–	4	3	4	1[3]
Harvesting of straw	1[1]	1[1]	1[4]	1[3]	–	–	1[3]	–	–	–	–
Transport to the stores	2	2	2	2	1	1	2	4	3	4	1

[1] Only in the treatment wL.
[2] Only in the treatments wL, FYM, US and DS.
[3] Only in the treatments DS + FR, DS + FER, wL-FR and wL-FER.
[4] Only in the treatments DS + FR and DS + FER.

spring within the same crop rotation as manures for the nonlegume crops.

The biogas systems with the use of off-farm purchased substrates (DS + FER and wL-FER) were modeled on the basis of silage maize derived from dedicated energy crops. As reference yields (Table 3), the results of the field trials reported by Möller et al.[14] for series I and by Stinner et al.[13] for series II were used.

LCI analysis

The inventory analysis consists of the recompilation of data concerning energy consumption, emissions and products resulting from each activity in the production system. Data of each process were collected and allocation, to the farm compartments animal production, plant production and energy production, were performed. The present analysis included the extraction of raw materials (e.g., fossil fuels and fertilizers), the production and transportation of farming resources (e.g., fertilizers, seeds and fuels) and all agricultural operations in the field (e.g., manure application, tillage and harvest) and related emissions as recompiled in Table 2. The related consumption of fossil fuels was assessed according to data in the literature[24,25]. All calculations were performed for a reference farm of 200 ha, and refer mainly to German conditions and the state-of-the-art technologies. The use of farm machinery was calculated for a mean field area of 5 ha and fitted according to our own records and supplemented by data available in the literature[24,25]. Total production of plant products (grains + tubers), milk and electrical energy are presented in Table 3. It was calculated that mineral nutrient outputs (phosphorus and potassium) by sold products were replaced by an equivalent amount of purchased mineral nutrients, e.g., by spreading rock dusts. Furthermore, the application of 200 kg lime ha^{-1} yr^{-1} to keep soil at optimal pH was assumed. For the modeled cropping systems, it was assumed that pesticides were only applied to potatoes (250 g active ingredient ha^{-1}). The environmental impact related to the preparation of the mineral fertilizers, pesticides and for the production of the required seeds and seed tubers was considered according to data reported in literature[26]. With respect to LCI of electricity, the German mixture was used. A primary energy input of 2.654 MJ per MJ electricity, and specific gaseous emissions of 172 g CO_2, 0.348 g CH_4, 5.04 mg N_2O and 2.78 mg NH_3 per MJ electricity, or 0.0502 kg CO_2-equiv. kWh^{-1} electrical energy were assumed[26].

The requirement of electrical energy for dairy husbandry was calculated according to data provided by Clausen[27]. The requirement for fossil fuels (diesel) was set at 22.5 liters of livestock unit^{-1} yr^{-1}.[28] The environmental impact for production and disposal of the used electrical energy and fossil fuels was estimated according to data available in the literature[26]. The feeding plan was compiled according to available data[29,30]. The milk yield per cow was set at 7000 kg milk yr^{-1}.

It was assumed that digestion and storage of slurry and effluents were carried out in tanks made from reinforced concrete. The digestion period depends on the kind of substrate and its biodegradability: (1) 30 days for digesters with high inputs of liquid animal slurries and low additions

Table 3. Total production of plant products (grains+tubers), milk and electric power.

	Series I					Series II		
	FYM	US	DS	DS+FR	DS+FER	wL	wL FR	wL FER
Plant products (t dry matter ha^{-1})[1]	1.01	1.05	1.04	1.08	1.06	3.67	3.93	3.93
Milk (kg fresh matter ha^{-1})	5649	5600	5705	5884	6397	0	0	0
Electric power (kWh ha^{-1})	0	0	800	2040	7000	0	2080	6800

[1] Without fodder.

Table 4. Amounts of biomass for digestion in the biogas plant (t fresh matter yr^{-1}).

		Series I			Series II	
Substrate	**DM content (%)**	**DS**	**DS+FR**	**DS+FER**	**wL-FR**	**wL-FER**
Slurry	9	2.400	2.400	2.400	0	0
Clover grass	33	0	0	0	690	690
Cover crops	10	0	540	540	760	760
Crop residues (straw)	86	0	290	290	450	450
Silage maize	33	0	0	2080	0	2080

DM, dry matter.

of other kind of residues; (2) 35 days for digesters with digestion of slurry and high amounts of other kind of substrates; and (3) 45 days for digesters without slurry as substrate. It was assumed that effluents were stored in covered tanks. The assumed capacity of stores allowed the storage of slurry and effluents for a period of 210 days. Electrical energy production was achieved by the use of a combined block heat and power plant (CHP). The amounts of substrates digested are summarized in Table 4. It was assumed that the storage of stable wastes was performed in open stores, if no digestion was carried out. Further, it was assumed that milk cows spend the entire year in the stable and the adjacent outdoor run.

The analyses of biogas systems include inputs and emissions from energy input in the entire biogas production chain. For example, a biogas digester has a need for electrical energy, for example, to power pumps, bubbler and control technology. It was assumed that the biogas digester has a requirement for electrical energy equivalent to 10% of the produced electricity. The heat used in the biogas plants was assumed to be produced from biogas in the CHP unit. The transport of the purchased substrates (silage maize) was assumed to be carried out in trucks. The average transport distance was assumed to be 20 km.

The environmental impact of providing and consuming fossil fuels and imported maize silage as substrate for biogas digestion was calculated according to Ecoinvent[26]. Methane oxidation by soils was estimated according to the data published by Boeckx and van Cleemput[31]. The N_2O background emissions of soils were calculated according to Neufeldt (Deutsches Biomasse-Forschungs-Zentrum gGmbH, Leipzig, pers. comm. 2005). Furthermore, N_2O emissions related to the application of organic manures (stable wastes, effluents of the biogas digester, crop residues and green manures incorporated into the soil) were included in the GHG inventory. Data published by IPCC[32,33] were used. According to these data, 1.00% of the applied manure-N was emitted as N_2O after soil application. For series II, the data regarding the differences in clover/grass-ley management published by Möller and Stinner[11] were used. Ammonia emissions related to spreading liquid manures were considered according to data published by Søgaard et al.[34]. Emissions after the application of FYMs were calculated according to data by Hutchings et al.[35].

The assessment of methane emissions derived from animal rumen and excrements was carried out according to data by IPCC[33], based on the gross energy intake. Emissions of N_2O from excrements in the stable were assumed to be negligible. Emissions of ammonia from the stable were considered according to data provided by Poulsen et al.[36] and Olesen et al.[37]. Calculations of N_2O and CH_4 emissions from manure storage (liquid and solid manures) were performed according to the data of IPCC[36]. However, for the inventory of ammonia emissions, data by Olesen et al.[37] were used, because no data were recorded in IPCC[33].

The environmental impact of construction and dismantling of the biogas digester was calculated according to Ecoinvent[26]. According to the available data[37], it was assumed that 1.8% of the methane produced in the digester was lost to the atmosphere due to leakages. The transformation of biogas to electrical energy in the CHP unit was connected to further emissions, which were estimated according to published data[38]. Savings on emissions from consumption of fossil fuels due to the produced renewable electrical energy were accounted as credits. Only electrical energy was balanced, assuming that there is no use for the heat energy.

The inventory of the impact category groundwater quality of the LCA was assessed by the N farmgate

Table 5. Data sources for resource consumption and emissions related to the different sub-systems.

Resources/emissions	Sub-system	Data source
Fossil fuels	Transportation	KTBL[24,25], ECOINVENT[26]
	Farm machinery use and production	KTBL[24,25], ECOINVENT[26], Clausen[27]
	Seeds	ECOINVENT[26]
	Production plant protection agents	ECOINVENT[26]
	Electrical energy production	Nill[40]
Minerals (phosphate rock and potash), lime	P-, K-fertilizer and lime production	ECOINVENT[26]
CH_4, CO_2, CO, NO_x, SO_2	All sub-systems[1]	UBA[41], Boeckx and van Cleemput[31], IPCC[33]
NH_3	Stable emissions	Søgaard et al.[34], Olesen et al.[37]
	Arable farming (volatilization)	
N_2O	Farmland (denitrification)	Neufeldt (Deutsches Biomasse-Forschungs-Zentrum gGmbH, Leipzig, pers. comm. 2005), IPCC[32,33]
NO_3^--N	Arable farming (leaching)	DBG[39], Brentrup et al.[42]

[1] Emissions due to energy consumption and direct emissions in all sub-systems, including direct emissions from stable and farmland.

balance, based on a method developed by the German Soil Science Association[39]. The components of the farmgate balance for N were the N input by biological N_2 fixation, by the purchase of seeds and biogas substrates, the N output via sold animal and plant products, and the gaseous N losses in the entire field–stable–field chain. Biological N_2 fixation and gaseous N losses were assessed as described by Möller[17].

LCIA

In a third step, an LCIA is required in order to evaluate the inventory data. Within the LCIA, the different inputs and outputs are summarized into environmental effects, the so-called impact categories. During this weighing step, each normalized indicator value is multiplied by a weighing factor, which represents the potential of the respective impact category to harm resources, natural ecosystems and human health. The data sources for resource consumption and emissions related to the different sub-systems are presented in Table 5. Calculations of the environmental impact of the use of fossil fuels were also carried out using published data[26]. For the impact category 'climate change', CO_2, N_2O, CH_4 and NH_4 emissions are aggregated (in CO_2-equivalents) using data published by IPCC[32] (for CO_2, 1; CH_4, 21; NH_4, 4.01; N_2O, 310; period of time, 100 years). To calculate the acidification potential of the different trace gases emitted by the modeled cropping systems the SO_2-equivalent factors (for SO_2, 1; NO_x, 0.7; NH_3, 1.88; HCl, 0.88; HF, 1.6; H_2F, 1.88) and for calculating the eutrophication potential the PO_4-equivalent factors (for NO_x, 0.13; NH_3, 0.35) were used[43].

In order to compare the systems, during the second step in LCIA, a functional unit was introduced, which describes the primary function fulfilled by a product system and enables different systems to be treated as functionally equivalent[44]. This study relates all resource consumption and emissions to 1 ha farmland. We chose the impact categories energy use, climate change, acidification, eutrophication and groundwater pollution (Table 6).

Table 6. Environmental impact categories and indicators considered in the LCA.

Impact category	Environmental indicator
Resource consumption	
Energy	Use of nonrenewable energy and production of energy
Mineral nutrients	Use of P- and K-fertilizer, lime
Climate change (= GWP)	CO_2-, CH_4-, N_2O-emissions (in CO_2-equivalents)
Soil function	
Acidification	NH_3-, NO_x-, SO_2-emissions (in SO_2-equivalents)
Eutrophication	NO_x-emissions N- and P-surplus (in PO_4-equivalents)
Water quality	
Ground water (nitrate leaching)	Potential of nitrate leaching, N-farmgate balance

Results

Consumption of fossil fuels

In series I, the main requirements per ha of farmland are related to production of plant biomass (Fig. 1). The digestion of slurry (DS) was related to additional energy consumption due to the resources required for digestion and for construction and removal of the digester. However, the credits for the offsets of fossil fuel emissions by the produced electrical energy led to a balanced result, indicating nearly energy self-sufficiency of the modeled farming system.

The harvesting of organic residues like crop residues and cover crops for digestion, in addition to the stable wastes (DS + FR), increased the total energy inputs in comparison with the reference system US, due to higher energy consumption related to the operations of the engine to produce electrical energy, as well as due to additional transport of substrates and the spreading of the effluents back on the farmland. However, it nearly triples the energy yields of the

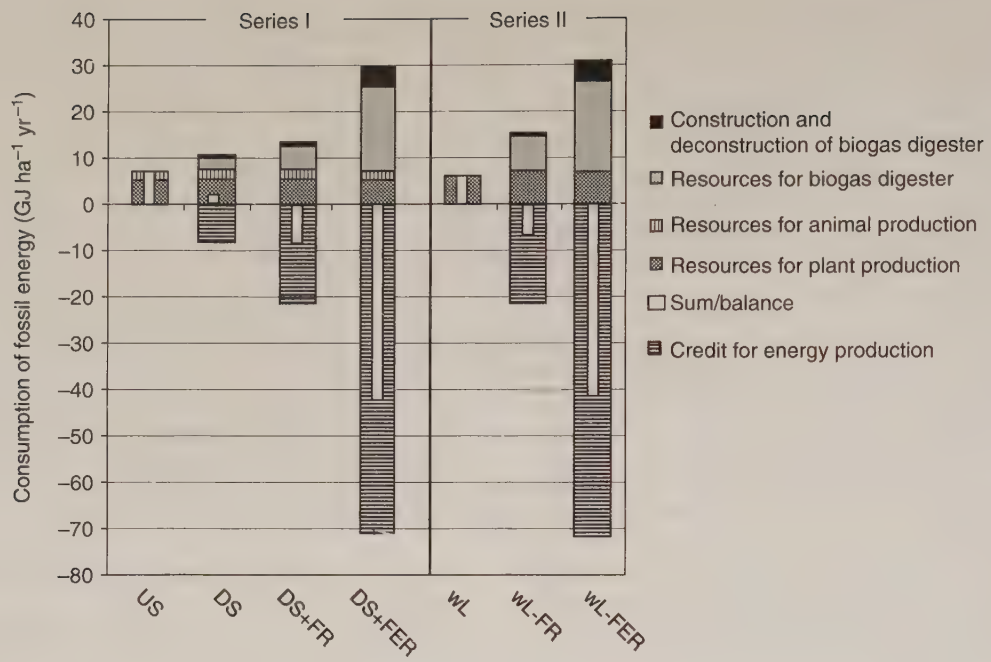

Figure 1. Inventory of the impact category primary energy consumption of the LCA (GJ ha^{-1} yr^{-1}).

cropping system (from 8.2 to 21.4 GJ ha^{-1} yr^{-1}). The total balance of the system indicated that more fossil energy was produced than consumed in such a system. The comparison of the additional energy needs for the biogas system and the amount of energy obtained by digestion indicated that a net energy yield (i.e., gross energy output minus energy input) of approximately 15 GJ ha^{-1} yr^{-1} of electrical energy was obtained. Approximately one-half of this energy was needed to meet the total energy demand for production of milk and plant products. The overall energy net surplus was 8.0 GJ ha^{-1} yr^{-1} (without use of the heat energy). The use of substrates of external provenance in DS + FER increased the energy yields dramatically, leading to a net surplus of 41.9 GJ ha^{-1} yr^{-1}.

In series II, the reference system wL showed similar requirements for energy per area as the reference systems in trial series I. The digestion of residues (wL-FR) dramatically increased the total energy requirements per area, due to the additional transport of substrates and the inputs needed for the operation of the digester. The energy yield was very similar to DS + FR (21.6 GJ ha^{-1} yr^{-1}). Accounting for the additional energy needs for operation of the biogas system and the amount of energy obtained by digestion indicated that a net yield of approximately 12.5 GJ ha^{-1} yr^{-1} of electrical energy was obtained. Approximately one-half of this energy was needed for production of plant products. The net energy surplus was 6.3 GJ ha^{-1} yr^{-1}. The additional digestion of purchased silage maize (wL-FER) led to very similar results as described for DS + FER.

Global warming potential (GWP)

Results showed that in the systems with dairy farming, methane emissions are the most important GHG emitted by the undigested reference system US (approximately 60%), whereas nitrous oxides are the most important GHG in the FYM reference system (approximately 54%) as well as in the stockless reference system wL (71%). Furthermore, the often preferred stable housing system in organic farming systems, the FYM system, showed the highest negative impact on GHG emissions (Table 7). The main reason was the much higher nitrous oxide emissions from manure handling in FYM systems than in liquid manure systems (US). Digestion of stable wastes (DS) significantly reduced the direct GHG emissions from animal husbandry in comparison with the reference system US. The main effect of digestion of stable wastes is the reduction of emissions of methane from 1921 in US to 1159 kg CO_2-equivalent emissions ha^{-1} in DS. Without accounting the credits for the substituted fossil fuels, the reduction was 15% for DS. However, displaced fossil fuel was the largest GHG sink. The inclusion of the credits means a reduction of 32% in the total balance of GHG emissions for DS. The additional digestion of crop residues (DS + FR) also reduced the GHG emissions from animal husbandry. However, digestion increased the GHG emissions from arable land. Two factors influenced the balance: (1) higher emissions due to additional processes for harvest and transportation of the substrates and return of the effluents as manures to the fields; and (2) higher emissions of ammonia after spreading manures. No losses of ammonia-N during digestion, and the higher ammonia concentration of effluents in comparison with undigested slurry stored in uncovered storage tanks, lead to higher emissions after spreading (DS). Furthermore, in DS + FR higher total amounts of N and higher amounts of ammonia were spread on the field as effluents, leading to higher emissions of ammonia.

Table 7. Inventory of the impact category GWP of the LCA.

		Series I					Series II		
	Gas	FYM	US	DS	DS+FR	DS+FER	wL	wL-FR	wL-FER
Direct emissions from plant production[1]	CO_2	0	0	0	0	0	0	0	0
	CH_4	−38	−38	−38	−38	−38	−32	−32	−32
	N_2O	420	458	507	461	614	618	376	554
	NH_3	16	23	32	44	59	0	42	57
Emissions related to resources for plant production[1]	CO_2	348	348	354	373	352	349	467	448
	CH_4	5	5	5	6	5	5	8	7
	N_2O	70	70	70	70	70	73	182	182
	NH_3	3	3	3	3	3	3	8	8
Direct emissions from animal production[1]	CO_2	0	0	0	0	0	0	0	0
	CH_4	446	1921	1159	1159	1159	0	0	0
	N_2O	2277	111	0	0	0	0	0	0
	NH_3	72	24	10	10	10	0	0	0
Emissions related to resources for animal production[1]	CO_2	129	129	129	129	129	0	0	0
	CH_4	4	4	4	4	4	0	0	0
	N_2O	1	1	1	1	1	0	0	0
	NH_3	0	0	0	0	0	0	0	0
Emissions related to resources for biogas digester[1]	CO_2	0	0	234	459	1594	0	635	1698
	CH_4	0	0	70	168	516	0	176	522
	N_2O	0	0	1	2	419	0	3	420
	NH_3	0	0	0	0	16	0	0	16
Emissions related to construction and deconstruction of biogas digester[1]	CO_2	0	0	34	48	247	0	52	245
	CH_4	0	0	1	1	6	0	1	6
	N_2O	0	0	0	0	2	0	0	2
	NH_3	0	0	0	0	0	0	0	0
Gross emissions for each GHG[1,2]	CO_2	477	477	751	1009	2322	398	1154	2391
	CH_4	417	1892	1201	1300	1652	−25	153	503
	N_2O	2691	640	579	534	1106	800	561	1158
	NH_3	91	50	45	57	88	8	50	81
Savings/credit due to energy production[1]	CO_2	0	0	528	1381	4607	0	1397	4623
	CH_4	0	0	23	59	197	0	60	197
	N_2O	0	0	5	13	42	0	13	42
	NH_3	0	0	0	0	0	0	0	0
Net emission for each GHG[1]	CO_2	477	477	223	−372	−2285	398	−243	−2232
	CH_4	417	1892	1178	1241	1455	−25	93	306
	N_2O	2691	640	574	521	1064	800	548	1116
	NH_3	91	50	45	57	88	8	50	81
Net total GHG balance[1]		3676	3059	2020	1447	322	1181	448	−729

[1] kg CO_2-equivalent emissions $ha^{-1}\,yr^{-1}$.
[2] Without savings/credits for the production of renewable energy.

The inclusion of credits means a total reduction of GHG emissions of approximately 50% for DS+FR in comparison with US. Additional digestion of silage maize in the treatment DS+FER increased the direct emissions from plant production (higher gaseous N emissions, higher amounts of transported effluents, higher amounts of soil-borne N_2O emissions due to higher amounts of manure application) and emissions for operating the biogas digester. Simultaneously, the credits for the substitution of higher amounts of fossil energy are significantly higher. Concerning the transportation of substrates, this operation will have only a limited impact on the various emissions analyzed here, provided the mean transportation distance is 20 km.

In the trial series II, the digestion of the available biomass residues (wL-FR) was related to an increase of GHG emissions per area of farmland (+51%), mainly due to the resources necessary to operate the biogas digester (Table 7). Digestion of organic residues led to a significant decrease of direct emissions from plant production, mainly due to the lower soil-borne N_2O emissions after removing the clover/grass-biomass and the cover crop biomass[11]. Accounting for the credits for the displaced fossil fuels, the total emissions per area were reduced by 59% in relation to the reference system without digestion (wL). The inputs for construction and dismantling the biogas digester slightly influenced the GHG balance, in both trial series.

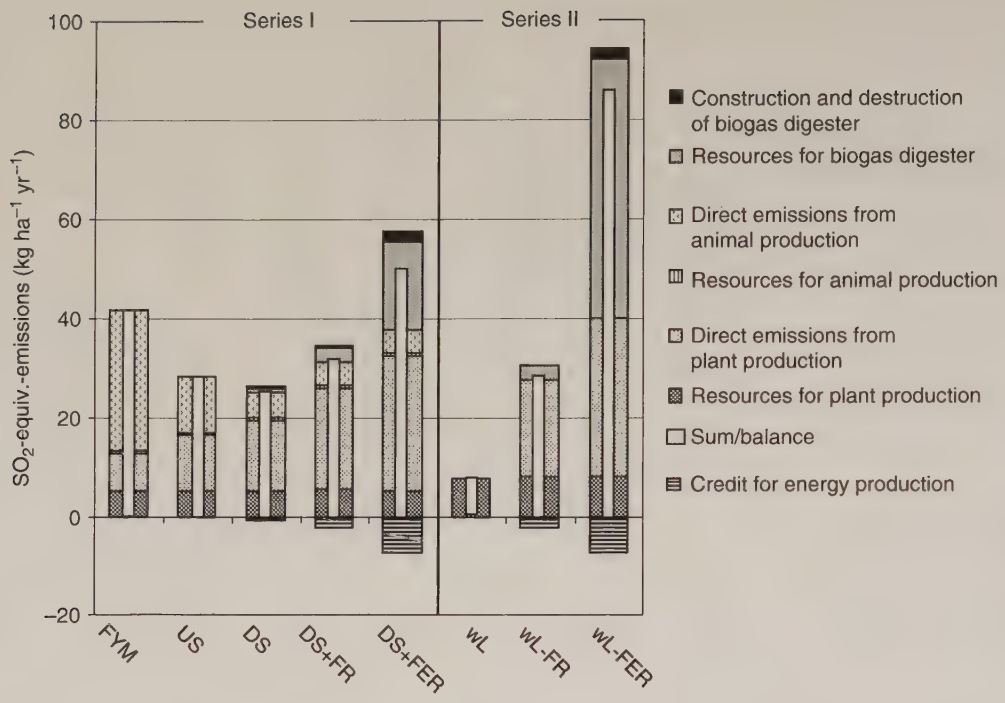

Figure 2. Inventory of the impact category acidification potential of the LCA (kg SO_2-equiv. emissions ha^{-1} yr^{-1}).

Acidification and eutrophication

The comparison of both reference systems FYM and US showed higher emissions with acidification potential for FYM than for US (Fig. 2). This was mainly related to higher N losses during storage of the stable wastes. Digestion of stable wastes prior to returning the effluents as manure to the fields strongly reduced the emissions with acidification potential related to animal husbandry (due to the reduction of emissions from stable wastes). However, the emissions of plant production were strongly increased, due to the fact that more N was applied, and the higher ammonia-N concentration in digested effluents. Both boosted ammoniacal-N emissions after spreading manures. As a consequence, digestion of stable wastes (DS) only slightly influenced the total balance.

The additional digestion of biomass residues from arable land (DS+FR) increased the emissions with acidification potential, mainly due to the fact that more manures were applied on soils as effluents of biogas digestion (higher gaseous N losses). Similar results were found for wL-FR, as well as for DS+FER and wL-FER. The influence of the credits for the replaced fossil fuels only slightly influenced the total balance in biogas systems.

Figure 3 reveals the results of the inventory of emissions with terrestrial eutrophication potential. The results showed a very similar picture compared with the acidification potential. This is due to the fact that NH_3 and NO_x contribute to both environmental effects.

Groundwater pollution and nitrate leaching risk

Potential nitrate leaching assessed according to the farm-gate N balance differed in both trial series, mainly depending on whether purchased substrates were introduced or not (Table 8). In trial series I, lowest values were assessed for the treatments FYM and DS+FR. The US and DS systems showed slightly higher values. A large increase was found for DS+FER. In trial series II, very similar values were found as reported for trial series I. Digestion of crop residues (wL-FR) reduced nitrate leaching potential by approximately 10%, whereas the inclusion of purchased substrates largely increased nitrate leaching potential. The assessed relation of nitrate leaching potential and measured soil mineral N contents in autumn at the beginning of the leaching period[11], did not fully match. For example, via the LCA methodology a higher nitrate leaching potential was found for US and DS in comparison with FYM. However, measured soil mineral N content did not differ between the FYM and the US and DS treatments. Furthermore, the slight increase of soil mineral N content in both systems with purchased substrates (DS+FER and wL-FER) did not match with the assessed large increase of the potential nitrate leaching via the LCA methodology.

Discussion

The results concerning the higher total GHG emissions in FYM compared to US (Table 7) matched well to other statements in the literature: Külling et al. calculated that for the daily manure amount per cow, GHG emissions from manure stored for 5–7 weeks were higher in the farmyard manure system (2.4 kg CO_2 equivalents) than in the liquid manure (1.5 kg CO_2 equivalents) system[45]. Substantial emission of nitrous oxide occurred with farmyard manure, which also had the highest methane values and, consequently, by far the highest GWP[46]. Slurry stores

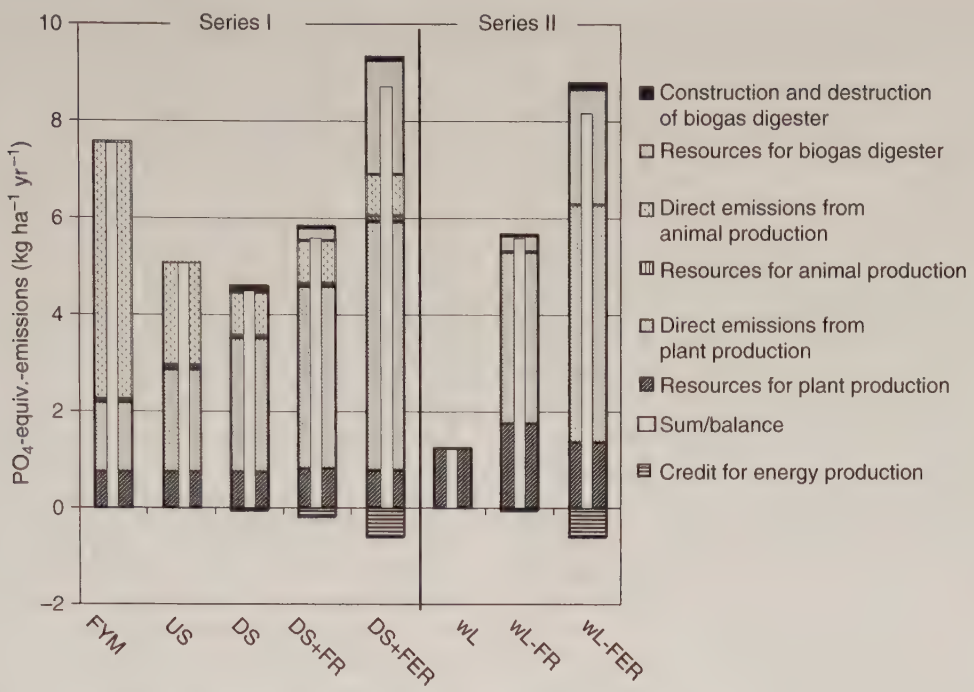

Figure 3. Inventory of the impact category terrestrial eutrophication potential of the LCA (kg PO_4-equiv. emissions $ha^{-1}\,yr^{-1}$).

produce only little N_2O because slurry generally contains neither nitrate nor nitrite[47]. Therefore, changing from FYM to liquid slurry systems has been suggested as a GHG mitigation option[48]. However, slurry systems are often criticized in the organic farming community because of concerns about soil fertility and animal welfare. However, newer comparisons of the balances of the total soil organic dry matter (DM) inputs for manuring systems based on the use of FYM in comparison with liquid slurry indicated that slurry-based systems provided soils with higher amounts of organic DM and carbon, if in the FYM system no straw was purchased from surrounding farms to meet the needs of straw for bedding animals[17]. Large amounts of organic carbon (and N) in FYM systems get lost due to their partial decomposition during storage[17]. Even when the slurry was digested prior to its application to soil, the overall soil carbon and organic DM inputs via manures, stubbles and other biomass residues were only slightly affected[17]. Concerning animal welfare of cattle, it appears that there are some alternatives to straw available, which may provide floor-comfort equal to that of straw[49]. Another option to improve FYM systems from an environmental point of view is to introduce the farmyard manure after removal from the stable into a biogas digester instead of the usual storage in heaps.

Furthermore, the results of the present study indicated that the implementation of a biogas digestion system has the potential to be a very effective and efficient strategy in combating several of today's environmental problems in agriculture, as also reported by others[50,51]. The implementation of biogas systems may lead not only to reduced gaseous emissions when fossil fuels are substituted but also to indirect benefits from changed handling of animal wastes and organic crop residues. The most significant impact of the anaerobic digestion of liquid dairy cattle manure with biogas capture and utilization is the reduction of the emissions of methane from store to the atmosphere. Furthermore, biogas digestion allows the use of a lot of different substrates like clover/grass-ley, crop residues and cover crops, which represent, until now, a large unexploited energy potential. As stated by Möller[17] and references therein, organic farming systems are very often N limited, and not carbon limited, and therefore a large potential for use of the circulating organic carbon for energy production is available in such systems. Digestion would provide additional revenue from the available organic DM in residues. Further benefits of digestion of residues are an increase of the amounts of mobile manures which can be allocated freely within the cropping system to the crops with highest N demand[13,14]. Regarding the effects on soil life, investigations within our own field experiments related to the soil carbon metabolism, e.g., total carbon content, water-extractable carbon, soil microbial biomass carbon and carbon substrate utilization test, did not reveal any significant differences between the performed manuring treatments[17,52], in spite of very large differences in soil DM inputs via organic amendments (stable wastes, biogas effluents, crop residues and green manures)[17]. These results showed that the different organic manuring treatments performed during a period of 4 years did not affect measurably soil N or soil carbon metabolism. It can be concluded that digestion of residues could lead to a win–win situation by reducing GHG emissions, implementing a new product (energy), and simultaneously by increasing food yields due to a better allocation of the available N in space and time.

Table 8. Inventory of the impact category groundwater pollution (N balance) of the LCA ($kg\,N\,ha^{-1}$).

	Series I					Series II		
	FYM	US	DS	DS+FR	DS+FER	wL	wL FR	wL FER
Purchased seeds and substrates	3	3	3	3	43	4	4	44
Biological N_2 fixation	132	136	136	134	139	120	137	133
N export sold products	44	46	46	48	50	72	78	75
Gaseous N losses	33	28	31	33	37	0	15	19
Potential nitrate leaching	57	65	62	56	92	53	49	83
Soil mineral N content in autumn in 0–90 cm[1]	48.7b	45.8ab	46.6ab	42.0a	48.5b	52.4b	43.4a	48.2ab

[1] As published by Möller and Stinner[11]; values of soil mineral N content only serve as an additional indicator that is not part of the balance sheet.

The net GHG emissions of $3.9\,Mg\,CO_2$-equiv. ha^{-1} farmland in the reference system FYM and $3.2\,Mg\,CO_2$-equiv. ha^{-1} farmland in US are lower than the 5.6–7.3 Mg CO_2-equiv. ha^{-1} farmland (Table 7) found by others[53]. Olesen et al.[2] found emissions of organic dairy farms ranging between 3 and 9 Mg CO_2-equiv. ha^{-1}. The lower GHG emissions found in the present study were related to the fact that a mixed farming system with milk and plant production was modeled. Arable cropping systems emitted much less GHG per unit area than mixed farming systems with arable crops and animal husbandry, as shown, for example, by results with the reference system wL in trial series II.

As shown by results presented in Figure 1, digestion of stable wastes and crop residues allowed a net self-sufficiency concerning energy inputs, or even a net energy surplus from using such kind of wastes. Using biomass waste from food production for energy production in a biogas digester eliminates the negative side-effects of open stable waste storage (Table 7) or soil incorporation of large amounts of biomass in autumn prior to the main leaching and denitrification period[11] and generates useful heat and electrical energy as well. Also other studies highlight the value of bio-energy from waste products, because they are not related to any substantial land use change and its emissions[54,55]. For example, Thyø and Wenzel[56] concluded that biogas from manure implies by far the highest reduction of GHG emissions per unit of services provided to society. The comparison of the net energy yields from organic residues obtained within the present cropping system to dedicated energy maize silage for biogas digestion showed that the obtained net energy yields from digested wastes from food and animal production correspond to approximately 20–25% of the yields on a per hectare basis obtained with dedicated maize silage[57,58], or even approximately 50% in comparison with agro-fuels from rape seed[57], however, without displacement of production of food crops. Owing to the implementation of crop rotations with a high percentage of fertility-building crops and large amounts of organic residues, organic farming systems mostly have a large surplus of organic carbon for soil humus production, which could be partially used for production of energy[17]. Also biogas digestion mainly metabolized the easily degradable organic carbon compounds of biomass, while the lignocellulosic residues, which are needed for enhancing and sustaining soil quality[59,60] were not degraded or degraded only to a low extent in a biogas digester[61].

When biogas systems are designed to use dedicated energy crops (DS-FER and wL-FER), a large increase in net energy yield (i.e., gross energy output minus energy inputs) could be achieved. However, the production of energy from dedicated main crops means competition between food production and the production of energy, which has led to the discussion of potential problems regarding land use competition[54,55,62]. A further point of criticism addresses the emissions and energy balance of energy obtained from dedicated energy crops. Some authors reported a low net energy yield and an unsatisfactory long-term sustainability performance of energy produced from dedicated plantations[55,63,64]. Double crop sequences of annual crops with an intercalated cover crop could also be used to improve feedstock production, while overcoming many of the liabilities associated with the use of dedicated energy crops. By pairing a cool-season cover crop with warm-season crops, dedicated biomass double crop sequences could provide soil cover for most of the year, offering the potential for increased biomass yields and reduced soil and nutrient losses compared with annual crop monocultures[65,66].

The acidification potential of a system, expressed in the present system as kg SO_2-equivalents, represents its contribution to the acidification of natural ecosystems like forests or lakes. The effects of biogas digestion of stable wastes on acidification and eutrophication was much less than found for the impact categories GHG and fossil fuel consumption. Furthermore, calculated acidification in SO_2-equivalents (Fig. 2) was much lower than the acidification potential of $107\,kg\,SO_2\,ha^{-1}$ found in the literature[53]. Similarly, the computed eutrophication potential (Fig. 3) was much lower than the values calculated for organic farms of $13.5\,kg\,PO_4\,ha^{-1}$ by Haas et al.[53]. The obtained results indicated that acidification was reduced when stable wastes were digested. This reduction was mainly induced by reduced N emissions during storage of stable wastes. Digestion of crop residues increased acidification and

eutrophication in both trial series, due to the partial ammonification of organically bound N during digestion, increasing the ammonia-N emissions after field spreading of biogas effluents.

Farmgate balances for N as an indicator for the potential groundwater pollution with nitrate indicated a significant impact of the treatment (Table 8). However, the comparison of data obtained from the farmgate balance approach and the experimentally measured data of soil mineral N content in autumn at the beginning of the leaching period (Table 8) showed that the N surplus approach, as commonly used for LCA studies, is only an indicator for the potential nutrient loss, but not for the actual nutrient loss, as also stated by others[67]. For example, cover cropping is a singly very effective measure to reduce the risk of groundwater pollution[11], which is not considered as a factor in LCA studies. The farmgate N balance was only slightly influenced by cover cropping; however, soil mineral N content was strongly influenced. Therefore, farmgate N balances for assessing potential groundwater pollution were only a weak indicator for groundwater pollution.

The construction and demolition of installations in a biogas plant produce hardly any damage to the environment, as also found by other studies[68].

Calculations performed in the present study used a lot of data available in the literature. In a few cases, the database was too weak to consider it in the calculations. For example, in the literature, there are some indications that ammonia was lost from biomass left on the field surface[69–74]. Published data ranged between 2.7 and 45.0% of biomass-N. Due to a lack of reliable data, those ammonia-N losses from plant biomass left on the field were not included in present LCA calculations. An inclusion would boost values of the inventory categories GHG, acidification and eutrophication of the reference systems, mainly for the reference system wL in trial series II (due to the high emissions reported for mulched clover/grass leys), but also for the reference systems FYM and US of trial series I, as well as for DS, where cover crops were left on some of the fields on the soil surface until mid–end winter. Another topic concerns the methane emissions from biogas plants. GHG balances were calculated for the biogas systems assuming that the final stores of the digested effluents are hermetically sealed and only 1.8% of the methane produced in the digester permeated the covers and were lost. However, most of the biogas plants in Germany did not have a covered effluents store. Calculations indicated for trial series I that the GHG-reducing effect of stable wastes digestion (DS) would turn negative, if approximately 28% of the produced methane was lost to the atmosphere. In the DS+FR system, emissions of *c.* 19% of the methane would mean that the GHG balance turned negative; in DS+FER, approximately 11%. In trial series II, with 10% emissions of methane in wL-FR and 9% in wL-FER, the GHG balance of biogas digestion would turn negative. A further uncertainty concerns the emission factor for N_2O emissions of soil-applied liquid and solid manures. Present calculations used the IPCC default value of 1.00% of the soil-applied N. Most of the manures were spread to soil in late winter and spring, when soils were moist. More recent results suggest that the N_2O emission factor for the organic manures with very moist soils was 2.5-fold higher than the default IPCC emission factor[75]. A higher emission factor would affect mainly the treatments with high levels of soil applied N, e.g., DS-FER and wL-FER. A further factor of uncertainty is the emission factor for N_2O emissions from solid manure heaps. The IPCC default value of 2% of the N amounts introduced into the store[32] was based on one study by Külling et al.[45], the uncertainty range was assessed with the factor 2.[32] Adoption of another default value would affect mainly the results for the FYM treatment, as the total GHG balance of this system was significantly affected by the total N_2O emissions during the storage phase.

Conclusions

The results of the present study indicated that the implementation of biogas systems may lead not only to reduced gaseous emissions when fossil fuels are replaced, but also to indirect benefits from changed handling of animal wastes and organic crop residues. Digestion of stable wastes has the potential to reduce mainly the net emissions of GHG, whereas the other effects per unit area on the other impact categories, like eutrophication and acidification potential, are rather small. Digestion of crop residues, cover crops and dedicated energy crops also lead to a reduction of net GHG emissions; however, it has the potential to increase the risk of emissions with acidification and eutrophication potential due to higher gaseous N emissions after manure spreading. Digestion of residues could lead to a win–win situation by producing a new product (energy), by reducing GHG emissions, and simultaneously by increasing food yields per unit area due to a better allocation of the available N in space and time. By using the residues available in an organic cropping system, approximately 25% of the net energy yields achievable with conventionally cropped maize dedicated for biogas digestion, and approximately 50% of the net energy yields achievable with conventional agro-fuel production by oil crops, could be obtained without replacement of food production.

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Changing human–ecological relationships and drivers using the Quesungual agroforestry system in western Honduras

Miguel Ayarza[1,*,†], Elisabeth Huber-Sannwald[2], Jeffrey E. Herrick[3,*], James F. Reynolds[4], Luis García-Barrios[5], Luis A. Welchez[6], Peter Lentes[7], Jellin Pavón[8], Jairo Morales[9], Anabel Alvarado[10], Mario Pinedo[11], Noemí Baquera[12], Sergio Zelaya[13], Rolando Pineda[14], Edgar Amézquita[1], and Marco Trejo[15]

[1]Tropical Soil Biology and Fertility Program, International Center for Tropical Agriculture, CIAT, Cali, Colombia.
[2]Division of Environmental Sciences, IPICYT, San Luis Potosi, México.
[3]USDA-ARS Jornada Experimental Range, Las Cruces, NM, USA.
[4]Nicholas School of the Environment, Duke University, Durham, NC, USA.
[5]Universidad Frontera Sur, ECOSUR, Chiapas, Mexico.
[6]FAO, Tegucigalpa, Honduras.
[7]Forage Project, CIAT, Tegucigalpa, Honduras.
[8]Instituto Nacional de Tecnología Agropecuaria, INTA, Managua, Nicaragua.
[9]Faculty of Natural Resources Management, Agrarian National University, Managua, Nicaragua.
[10]Department of Socioeconomy, Universidad Nacional de Agricultura, ENA, Honduras.
[11]National School of Forestry, ESNACIFOR, Honduras.
[12]New Mexico State University, Las Cruces, NM, USA.
[13]United Nations Convention to Combat Desertification, Bonn, Germany.
[14]Forestry Department, National School of Forestry, ESNACIFOR, Honduras.
[15]Dirección de Ciencia y Tecnología Agropecuaria, DICTA, Tegucigalpa, Honduras.
*Corresponding author: mayarza@corpoica.org.co and jherrick@nmsu.edu

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Abstract

Development of sustainable agricultural production systems in the tropics is challenging in part because the local and external conditions that affect sustainability are constantly in flux. The Quesungual agroforestry system (QSMAS) was developed in response to these changing conditions. The history and potential future of the QSMAS provide an opportunity to consider the factors affecting small-scale agricultural production systems on marginal lands throughout the world. We evaluated the QSMAS in Honduras in the context of the five principles of the Drylands Development Paradigm (DDP) during three periods: pre-QSMAS, QSMAS adoption and the future. The first two periods provided lessons that could be relevant to other regions. The QSMAS system in Honduras must continue to evolve, if long-term benefits are to be realized. We conclude that while the DDP was a useful framework for systematically identifying the critical drivers and processes determining the sustainability of QSMAS in Honduras, it is ultimately no more able to predict the future than the collective knowledge of those who choose to apply it. The DDP, however, can facilitate the integration and application of knowledge.

Key words: agroforestry, Quesungual, QSMAS, Drylands Development Paradigm, DDP, Honduras, sustainability, interdisciplinary

Introduction

Population growth and agricultural frontier expansion using slash-and-burn practices in the forested hillsides of subtropical to tropical areas have resulted in extensive reduction of forest cover, and increased runoff and soil erosion throughout the world and especially in Central America[1–4]. The resulting loss of soil productivity and biodiversity has exacerbated rural poverty, particularly in steepland areas that make up 78% of the total area of Central America[5]. For the past 25 years, reversing land

†Current address: Corporación de Investigación Agroepecuaria, CORPOICA, Bogotá, Colombia.

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degradation and increasing agricultural output have been a priority of numerous research and development projects. These efforts, while well-intentioned, have been mostly ineffective because of incomplete, poor understanding of the complex interactions between social, ecological, institutional, economic and policy factors that lead to land degradation and limit recovery[6].

The Quesungual agroforestry system (QSMAS) has been adopted since 1992 by thousands of farmers and helped many of the poorer farmers in the hillside region of Lempira, Honduras to achieve food security, while improving soil and water conservation[7]. This slash and mulch-based system combines selective thinning and pruning of native tropical forest vegetation with planting of annual crops (maize, sorghum and beans) and/or improved grasses with no burning, zero tillage/direct planting and spot fertilization. Compared to slash-and-burn, this system maintains permanent soil cover improving soil and water conservation. Since farmers use different criteria for selecting specific trees to thin and/or retain, the widespread adoption of the QSMAS system has resulted in a diverse landscape mosaic of tree cover. This helps conserve the deciduous tropical forest, which is often cited as one of the most highly threatened ecosystems in the world, now covering a small fraction of the area it dominated prior to European colonization[8]. Farmers in other regions of Latin America also practice variations of slash-and-mulch, including some in high-rainfall areas of Ecuador's Amazon Basin[9] and Costa Rica[10].

The widespread adoption of the QSMAS has been driven by observed increases in crop yields associated with the moderate use of fertilizers, better crop varieties, improved soil water availability[11] and significant reduction in costs associated with agrochemicals and labor[12]. In addition to increasing annual crop production, the improved capacity to capture, retain and slowly release water has allowed QSMAS farmers to escape devastating losses during droughts and hurricanes such as the severe El Niño drought in 1997. In 1998, after the devastating Hurricane Mitch in Central America, farmers practicing this system reported less soil, water and crop losses compared to those practicing the traditional slash-and-burn agriculture[13].

The evolution of the present day QSMAS provides a unique example of the integration of local environmental knowledge with national and international expertise through stakeholder cooperation[14]. While much international focus has been directed toward slash-and-burn approaches[15–17], there is little information on slash-and-mulch by comparison[18]. Although QSMAS is a potential model for developing sustainable agroforestry systems in other parts of Latin America and the world, its adoption by others is limited by a lack of a detailed, systematic analysis of the key biophysical and socio-economic drivers and variables involved. Furthermore, in order to establish guidelines for the QSMAS approach, input from all stakeholders is required. Guidelines for implementing the QSMAS need to include provisions for unanticipated consequences of adopting this technique, as well as the effects of potential changes in markets and environmental conditions[19].

Our general objective was to describe the QSMAS as practiced in the steeplands of western Honduras (Lempira) in the context of the principles of the Drylands Development Paradigm (DDP)[18]. We used the principles of the DDP to identify some of the critical socio-economic and biophysical factors causing land degradation[20] in Lempira and to evaluate the long-term sustainability of the QSMAS. Specifically, we (1) defined the socio-economic and biophysical conditions associated with the development of the QSMAS, (2) identified the factors that led to QSMAS adoption and (3) anticipated future challenges to the sustainability of the QSMAS.

Key Biophysical Characteristics of Lempira

The Lempira region is located in the southern part of Honduras close to the border with El Salvador (Fig. 1). It has an area of 2177 km^2 and is an important component of the Lempa River watershed, which provides nearly 60% of hydropower consumed by El Salvador. Soils of the region are predominantly Entisols with slopes greater than 30%, are shallow and acidic ($pH < 5.1$) with low soil organic matter content and available phosphorus[21] and have a gravely or stony loamy sand texture[22]. Although stones in the soil profile (which accounts for 30–50% of total soil volume in the 0–30 cm depth) reduce soil water holding capacity, surface stones can reduce runoff and erosion by dispersing the kinetic energy of raindrops and slowing overland flow[23,24]. The average annual temperature varies from 17 to 25°C. Annual precipitation ranges from 1400 to 2100 mm in the 600–900 m range of elevation, where the QSMAS is practiced. The rainy season extends from early May to the end of October. During the dry season from early November to late April, strong winds blow from the North and the enhanced evapotranspiration rates cause severe water deficits until the onset of rains.

Key Socio-economic Characteristics of Lempira

With limited support from the Honduran central government, Lempira is relatively isolated from the rest of Honduras due to a poor infrastructure of roads. It has a total population of about 110,000 inhabitants, and is considered to be one of the poorest regions of the country. Remittances from relatives working in the US constitute an important source of supplemental income for many families[25].

Farms are generally small; 80% are less than 5 ha[21] and only 25% of farmers own their land[26]. The rest are allowed to farm common lands without a formal land title. Seventy-five percent of the farmers grow maize and beans as subsistence crops with traditional slash-and-burn, generally producing very low yields (600–800 kg/ha maize and

Figure 1. Location of the study area in the Lempira region in Honduras, Central America.

300 kg/ha beans), and many households also raise chickens, pigs and some cattle. Some farmers allow livestock to graze crop residues at the beginning of the dry season. Local food markets in Lempira are limited and are poorly integrated with the rest of Honduras. Basic grain production is primarily for self-consumption and local delivery, although cross-border trade with El Salvador, which is the most densely populated and industrialized country in Central America, is rapidly increasing. Local labor is also limited, but informal labor exchange within Lempira is a common practice and seasonal migration takes place in the northern coffee-producing areas.

Assessing QSMAS

From 15 to 20 November 2005, an international team of 16 biophysical and social scientists, students, extension specialists, development workers and other stakeholders conducted a workshop in the Lempira region to conduct an analysis of the QSMAS within the context of the five principles of the DDP:

1. Human–environmental systems are coupled, dynamic and co-adapting, so that their structure, function and interrelationships change over time.
2. A limited suite of '*slow*' variables are critical determinants of human–environmental system dynamics.
3. Thresholds in key slow variables define different states of human–environmental systems, often with different controlling processes; thresholds may change over time.
4. Coupled human–environmental systems are hierarchical, nested and networked across multiple scales.
5. Maintenance of up-to-date, local environmental knowledge is the key to functional co-adaptation of human–environmental systems.

Although the DDP has its roots in the desertification literature[18,27], we believe its principles are relevant to all rural human–environmental systems in Latin America.

This case study was jointly organized by the Consortium for the Integrated Management of Soils of Central America (MIS) and ARID*net*, an international research network that is testing the robustness of the DDP via multiple case studies of land degradation throughout the Americas. The goals of ARID*net* include facilitating field-level interactions between researchers, local stakeholders (farmers, land owners and developers) and decision-makers (details available at URL: http://www.biology.duke.edu/aridnet/).

In addition to background information from published and unpublished literature on the QSMAS, the workshop team conducted numerous interviews of scientists, development workers, community leaders and farmers living in and near the town of Candelaria, where the QSMAS has been widely adopted. In order to better understand the factors associated with the adoption of the QSMAS, interviews were also completed in the vicinity of the neighboring town of Guarita, where slash-and-burn agriculture continues to be practiced. In 2006, 16 additional individuals were interviewed to obtain further details on specific topics, provide clarifications where needed, and to obtain additional information to address gaps in our knowledge.

Our evaluation was completed in two phases. The first phase involved all workshop participants and immediately followed the completion of the on-site interviews. Working groups with biophysical and socio-economic expertise were formed to systematically apply the key concepts of the DDP in order to evaluate: (1) the extent to which QSMAS is potentially reversing land degradation in the area, (2) to

identify the key biophysical and socio-economic variables associated with the evolution and success of the QSMAS and (3) to consider the extent to which the QSMAS will likely be an effective approach to limit land degradation and promote recovery given current farming trends in Lempira.

In the second phase, selected representatives of each working group refined this analysis to specifically cover three periods: *pre-*, *post-* and *future*-QSMAS. The *pre*-QSMAS period (1970–1990) represented a retrospective analysis focused on the conditions that led to the development of the QSMAS, the *post*-QSMAS period (1990–2006) covered the years since adoption of QSMAS to the present and the *future*-QSMAS period considered some of the most likely future challenges to the persistence and sustainability of the QSMAS in the Lempira region.

The QSMAS is a complex and dynamic system that consists of a suite of unique adaptive management systems being applied and modified by individual farmers. While this diversity makes generalizations more difficult, they also help explain the evolution of the QSMAS and point to its potential value in other parts of the world. In Table 1, we summarize the results of the application of the five principles of the DDP to each of three periods (*pre-*, *post-* and *future*-QSMAS).

Pre-QSMAS (1970–1990)

During the 1970s, the Department of Lempira experienced a rapid expansion of agricultural activities influenced by human and environmental drivers (DDP Principle 1): increasing population size (growth rate of 3% per year), migration from neighboring regions (including from El Salvador) and high poverty (90% of population lived on less than two dollars per day, 64% suffered of malnutrition and 90% were illiterate)[27]. Thousands of poor farmers practiced subsistence agriculture on more than 20,000 ha of communal forests using slash-and-burn farming. The extensive deforestation and overexploitation of these forests led to increased soil erosion (as much as 109 $Mg\,ha^{-1}\,yr^{-1}$)[11], reduced soil cover and decreased soil fertility and water holding capacity (DDP Principle 2), causing decreased food production (maize 500–800 kg/ha, beans 200–300 kg/ha and sorghum 400–700 kg/ha)[13]. In time, these factors drove production systems past a threshold beyond which they were not able to meet household needs for food (one family of eight people consumes 1500 kg maize and 400 kg beans per year) and were no longer resilient to droughts and soil fertility decline (DDP Principle 3). Isolation, poor health and education services and weak social organization triggered further land degradation and extensive migration of locals to urban areas and elsewhere in search of work (DDP Principle 4).

In the 1980s, the Honduran government initiated a program to solve the food crisis by introducing improved crop varieties and subsidizing inorganic fertilizers and herbicides for Lempira farmers. During this period, the use of chemical fertilizers and herbicides increased from 25 to 80% considering all farms[28]. Nevertheless, despite intensive promotion of this program by the government, it had limited success because of the lack of access by most farmers to capital and technical assistance (DDP Principle 5). Moreover, the practice of this type of agriculture on slash and burned fields often further promoted soil and water losses.

Post-QSMAS (1990–2006)

After the devastating effect of a severe drought in 1987, the Honduran government and FAO jointly pursued a new strategy in Lempira to both reduce poverty and to increase crop production, while promoting restoration and conservation of native tropical deciduous forest[26].

The QSMAS emerged as a product of a community-based learning process in which local indigenous knowledge pertaining to no burning, slashing, mulching and pruning of native forest vegetation was combined with technical knowledge (use of spot fertilization, improved crop varieties and zero tillage/direct planting) (DDP Principle 5). Local residents (e.g., farmers and teachers at the technical schools) and local government authorities worked together with development agencies to evaluate, adapt and integrate new and existing practices and knowledge to develop the QSMAS. The key guiding principle was to maintain adequate soil cover throughout the year. This was achieved through a variety of practices, including tree pruning and using crop residues as mulch, minimizing or eliminating tillage, and introducing improved seeds and targeted fertilizer applications[12]. As a result, on-farm maize and bean yields increased 54 and 66%, respectively[13] (DDP Principle 2). A recent report of a study conducted by scientists of the Centro Internacional de Agricultura Tropical (CIAT)—Tropical Soil Biology and Fertility (TSBF) Program comparing slash-and-burn with QSMAS plots of increasing age (2–10 years of use) confirmed the improved capacity of QSMAS to retain soil and water[22]. According to this study, soil loss in slash-and-burn plots was five times greater than in QSMAS plots. Water loss by runoff was 25–60% greater in slash-and-burn plots than in QSMAS plots. Conversely, water infiltration in QSMAS plots was 15–30% greater than in slash-and-burn plots.

Although the adoption process of QSMAS was initially driven by short-term increases in crop yields at the farm level, its widespread adoption by thousands of farmers can be explained on the basis of a complex interaction with three main drivers of development[29]:

1. *Collective action* to focus on capacity building of local and regional organizations to support small farmers and improve education (DDP Principle 2).
2. *Technological change* to increase the resilience of local and regional production systems (DDP Principle 3).
3. *Policies and incentives* to promote the adoption of new production technologies (DDP Principle 1).

Table 1. Summary of results of DDP-based analysis (19).

DDP principle Time frame	Pre-QSMAS (1970–1990)	QSMAS adoption (1990–2006)	Issues QSMAS must address in the future (2007–2020)
P1. Degradation always involves human and environmental drivers	*Human drivers:* • Increasing population growth • High poverty • Limited access to services	*Human drivers*: • Collective action • Policies and financial incentives	*Human drivers*: • Increasing integration to local and regional markets • Improved financial support for crop diversification • Increasing land value • Decreasing labor
	Environmental drivers: • Soil and water losses and loss of soil fertility	*Environmental drivers*: • Technological change	*Environmental drivers*: • Market-oriented sustainable production • Expanded area for livestock
P2. The critical dynamics of dryland systems are determined by 'slow' variables, both biophysical and socio-economic	*Human factors:* • Unsatisfactory levels of food production to meet household requirements	*Human factors*: • Increased food security at household level	*Human factors*: • Long-term profitability of crop/livestock production • Increasing value of land
	Biophysical factors: • Increasing deforestation rates • Loss of soil cover • Reduced water holding capacity	*Biophysical factors* • Increased water holding capacity • Increased soil cover and tree density	*Biophysical factors* • Livestock density • Demand for water and nutrients
P3. Slow variables possess multiple thresholds that, if crossed, cause the system to move into a new state or condition	*Socio-economic thresholds* • Seasonal food and water scarcity	*Socio-economic thresholds* • Food and water security • Enough fuel wood supply to meet household demands	*Socio-economic thresholds* • Increased value of the land • Payment for environmental services
	Biophysical thresholds: • Incapacity of eroded soils to recover its productivity • Collapse of the S&B technology.	*Biophysical thresholds* • New equilibrium between food production and forest conservation • Reduced soil and water losses	*Biophysical thresholds* • Adequate balance between crops, trees and cattle in the landscape • Maintain high biodiversity
P4. The objectives, connections between, and perspectives and attitudes of different stakeholders demand consideration of the multi-level, nested and networked nature of H-E systems	*Socio-economic*: • Isolation from markets and support services • Weak organization at the community and watershed scales *Biophysical:* • Soil and vegetation losses affecting water availability for downstream communities	*Multi-level connections* • Improved connection between short-term and long-term priorities at several scales: food production (household), water supply (community), health and education (municipality) and infrastructure development and provision of environmental services (basin)	*Country policies supporting*: • Greater freedom to trade with neighboring countries • Improved connectedness with markets through better infrastructure • True democracy to stimulate local initiative
P5. The key to maintaining functional co-adaptation of coupled human and ecological systems is an up-to-date body of 'hybrid' environmental knowledge that integrates local management and policy experience with science-based knowledge, all of which is mediated through an effective institutional organization	• Top-down approach to solve complex problems	• Bottom-up policies supporting no burning, improved water use and landscape conservation • Indigenous + technical knowledge to improve crop yields and resilience	• New knowledge needed to support intensification and diversification • Improved institutional and policy capacity to support changes

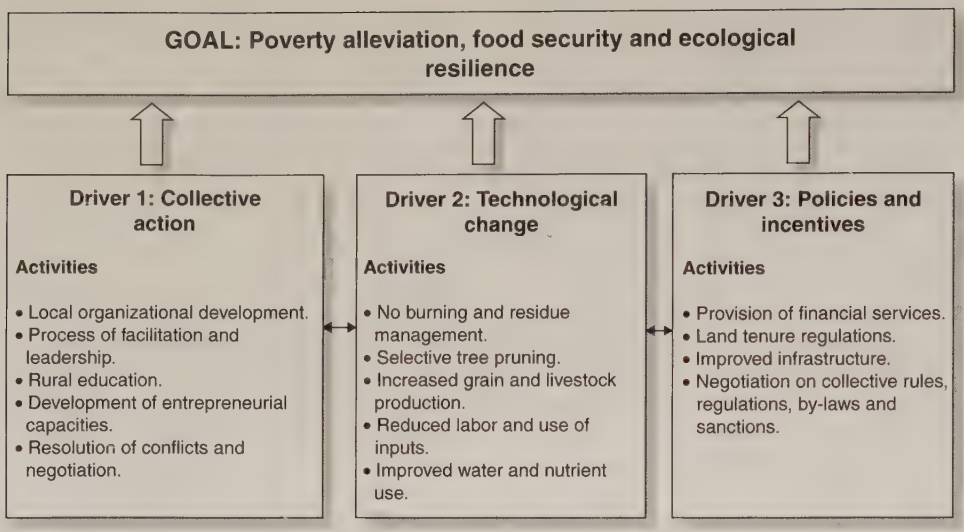
GOAL: Poverty alleviation, food security and ecological resilience
Driver 1: Collective action
Activities
• Local organizational development.
• Process of facilitation and leadership.
• Rural education.
• Development of entrepreneurial capacities.
• Resolution of conflicts and negotiation.
Driver 2: Technological change
Activities
• No burning and residue management.
• Selective tree pruning.
• Increased grain and livestock production.
• Reduced labor and use of inputs.
• Improved water and nutrient use.
Driver 3: Policies and incentives
Activities
• Provision of financial services.
• Land tenure regulations.
• Improved infrastructure.
• Negotiation on collective rules, regulations, by-laws and sanctions.

Figure 2. Drivers and activities associated with scaling up of QSMAS in the Lempira region.

Figure 2 shows the main activities associated with each driver. Adoption was also facilitated by farmer application of the 'Human Farm' principles developed by Elias Sanchez[30]. These principles emphasize that improved management of natural resources needs to be accompanied by the strengthening of human capital at the individual and community levels (DDP Principle 2).

With the support of FAO and several NGOs, local communities strengthened their capacity to negotiate incentives and benefits for the region (DDP Principle 4). Household heads organized water committees at the micro-watershed level to improve access to safe water. Local governments negotiated with the central government to implement long-distance learning radio programs (DDP Principle 4) and to improve the curricula of local schools and achieve better access to health services (DDP Principle 2). FAO and other development projects supported the formation of small co-operatives and financial services to strengthen the entrepreneurial capacity of men and women to transform and add value to their agricultural outputs and sell them through local and regional markets (DDP Principles 3 and 4). Access to rural finance enabled farmers to purchase better seeds, fertilizers and herbicides to improve crop production and invest in irrigation systems for subsequent diversification of their production systems[31].

Communal banks were another important financial mechanism supporting the implementation of the QSMAS. Their role was not limited to credit provision; they also served as a focus for collective action and enforcement of local policies. For example, credit was given only to farmers who did not burn their land. This new 'moral order' was supported by national and local laws forbidding the use of fire and protecting common forestlands and water reservoirs (DDP Principle 2).

This process caused a profound change in the organizational culture and structure of development in the region (DDP Principle 4). A new threshold of guaranteed food security, improved soil and water productivity and enhanced managerial capacity was reached as a result of a new balance between production and conservation (DDP Principle 3). The system resulted in a 27% reduction in labor requirements and an 18% reduction in land preparation and weed control[13]. At the landscape level, QSMAS contributed to the conservation of more than 40 native species of trees and shrubs[26] and the fields serve as sinks for methane with low emission levels of nitrous oxide[22]. Table 2 summarizes the main impacts of QSMAS in terms of land and water productivity (DDP Principle 2), forest conservation and local strengthening at household and community levels (DDP Principle 5).

Future-QSMAS

During the past 16 years, the widespread adoption of the QSMAS in the Lempira region has improved food security, water availability (DDP Principle 2) and has ensured an adequate supply of fuelwood for small farmers. More recently, however, the intensification and diversification of agriculture have been accelerated in response to increasing opportunities to sell to local and regional markets (DDP Principles 1 and 4). Although new markets bring new opportunities for farmers, they also pose some challenges. These changes can simultaneously lead to both increases and decreases in sustainability (DDP Principle 3), as the QSMAS is further modified. For example, some innovative farmers are planting introduced grasses under the QSMAS to intensify livestock production and others are simply increasing livestock consumption of crop residues. While the former can increase animal output and maintain or improve soil structure and fertility (DDP Principle 2), the latter could eliminate the hydrologic benefits of the QSMAS if protective soil cover were removed and soil compaction resulted (DDP Principle 3). Vegetable crop production with irrigation, stimulated by increasing trade

Table 2. Impacts and beneficiaries of the adoption of the QSMAS in the Lempira region (30).

Management component	Impacts	Beneficiaries
Increased soil fertility and agricultural productivity:		
1. Permanent soil cover	• Increased water holding capacity (from 8 to 29%) • Soil loss reduced from 300 to 16 $t\,ha^{-1}$	6000 small farmers practicing the QSMAS
2. Improved crop varieties	• Maize and bean yields increased by 30–40%	Farmers practicing the QSMAS
3. Five new grass species validated and disseminated	• Improved livestock production	Livestock producers
4. Two new feeding options for the dry season	• Increased milk production during the dry season	
Improved water quality and availability:		
1. Participatory watershed management	• More than 100 water committees and small irrigation projects established	1150 producers benefited by small irrigation projects
Sustainable management of forest resources:		
1. No burning	• 6000 ha managed without burning	6000 small farmers
2. Improved utilization of forest resources	• Local communities trained in the use of timber products	40 wood artisans
Improved entrepreneurial capacity:		
1. Improved financial availability	• 105 communal banks • Three cooperatives established • Three small milk-processing enterprises established	• 962 members benefited (55% men and 45% women) • Ten women's groups producing cheese
2. Entrepreneurial capacity enhanced	• Several financial systems developed	• 185 direct and 254 indirect jobs
3. Improved capacity to develop projects	• 648 development projects	• 20 municipalities
Education oriented to test and introduce innovations in Natural Resource Management (NRM):		
1. Rural education including innovations to improve land and water use	• Four communal technical institutes incorporate NRM principles in their curricula	• 867 students learn and apply new knowledge in 2001
2. New education materials available at local schools	• Four manuals	• 200 students of the Instituto Técnico Comunitario

with neighboring El Salvador, has the potential to increase cash flow, but these new production systems may require different soil and water management strategies (DDP Principle 4).

Other anticipated concerns, such as increasing pest and disease incidence (DDP Principle 3), will demand new knowledge and inputs (DDP Principle 5). In fact, anecdotal observations from researchers and farmer comments indicate that herbicide and insecticide use are already high in the areas that have adopted QSMAS. Another major concern is the increasing risk of more severe weather events (DDP Principle 3) that have been observed in the past because of climate change.

Although some intensification and diversification are clearly possible while maintaining the benefits of the current QSMAS, continuing co-adaptation of this human–environmental system will be required (DDP Principle 1) to maintain its resilience and benefits (DDP Principle 2), including improved water storage, recycling of nutrients and environmental services for downstream users. The discussion below focuses on key issues that QSMAS practitioners should consider if the benefits of the system are to be maintained.

Integration with markets

The construction of a bridge between the Lempira region and El Salvador during the 1990s was a key event (DDP Principle 3) that accelerated the integration of small farmers to markets and cross-border trade (DDP Principle 4). Small farmers practicing the QSMAS have benefited by selling their maize and bean surpluses at elevated prices. If international demand for maize continues to increase in the future, due to interest in the production of bio-fuels (DDP Principle 4), the pressure to increase production will rise, and farmers will need to learn how to further improve crop water and nutrient use efficiency (DDP Principle 5). Conversely, access to grain imports (whole and/or as industrialized products), coupled with labor shortage and off-farm income could reduce farmers, interest in local grain production, thus increasing livestock and open

grassland expansion in QSMAS-dominated areas (DDP Principles 1 and 3).

Improved rural financing

Access to formal and informal credit markets in the region should stimulate crop and livestock intensification of QSMAS. Farmers may reduce the area devoted to traditional crops and allow the introduction of new crop options with market potential using irrigation, improved storage facilities and improved varieties. Because of improvements in soil fertility and water availability under the QSMAS, crop and livestock production can be increased allowing further intensification of the system. However, indiscriminate increase of livestock can affect soil conditions, ground cover and tree density (DDP Principle 3). To be sustainable, intensification will have to be based on the strategic allocation of available soil and water resources under QSMAS to maintain an adequate tree density and soil cover and avoid soil compaction and erosion. A new cycle of technological change based on the combination of local and technical knowledge will likely be required to sustain an increase in crop and livestock production (DDP Principle 5).

Land value

Land ownership and value have been positively associated with the use of soil conservation practices[32], and in some cases the value of the land has increased because of the use of these practices (DDP Principle 2). This has been the case for land managed under QSMAS. Although there is no formal system to price the land in the region, farmers generally recognize that under QSMAS, land value is at least 30% higher than in areas without QSMAS (DDP Principle 3). This is a positive factor that may limit drastic changes of the system under intensification processes. Many farmers growing new crops on rented lands are now obliged to maintain permanent tree cover without burning.

Reduced labor

Family labor is decreasing due to the greater number of children attending school and the continuous out-migration of young people to the main cities in Honduras and USA (DDP Principle 4). This will become another factor influencing the intensification and diversification processes.

Toward a New Balance to Support Intensification and Diversification

If QSMAS is to continue to support the sustainable growth of the rural population in Lempira, a new balance between production and conservation will be needed (DDP Principle 3). This balance will require an optimum allocation in space and time of financial and land resources to support diverse crop and livestock production systems. Improved agricultural practices associated with the QSMAS will result, on the one hand, in enhanced productivity and resource quality and, on the other, in increased land value and reduced risks that will contribute to improved economic viability and social acceptance of the system in the long term (DDP Principle 2). This will require that local communities in the Lempira region learn to negotiate policies to ensure the benefits of improved land and water use for both upstream and downstream users. Economic benefits of improved water availability for downstream users should be shared with small farmers in upper catchments under a new arrangement (DDP Principle 4). Given the increased scarcity of both water and energy, this hydrologic benefit alone could support the adoption of the QSMAS. The alternative threshold will be of degradation and loss of resilience of the system if indiscriminate intensification of crop and livestock occurs without maintaining an adequate tree density and soil cover and avoiding soil compaction and erosion (DDP Principle 3).

The primary elements of the QSMAS—replacement of forest clearing, burning and tillage with thinning, pruning and direct planting—could be adopted and adapted in many parts of the world (Fig. 2). The key elements of the development process—honest participatory research and development—can also be usefully extended to other regions. However, adapting the system must be done carefully if long-term benefits are to be realized. As fresh water becomes scarcer, and demands for food and biofuel increase, it is also crucial to conserve biodiversity. To accomplish these goals simultaneously requires innovative approaches to crop production, such as described for the QSMAS to help restore degraded landscapes in Honduras. While the DDP is a useful framework for systematically identifying the critical variables and processes that determine the sustainability of any particular production system, it is ultimately no more clairvoyant than the collective wisdom of those who choose to apply it. The DDP can, however, help ensure that knowledge is integrated and applied.

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Effects of cultural system (organic and conventional) on growth and fiber quality of two cotton (*Gossypium hirsutum* L.) varieties

Dimitrios Bilalis[1]*, Sotiria Patsiali[1], Anestis Karkanis[1], Aristidis Konstantas[1], Marios Makris[2], and Aspasia Efthimiadou[1]

[1]Agricultural University of Athens, Department of Crop Science, Iera Odos 75, 11855 Athens, Greece.
[2]Thessaly Ginning S.A., Karditsa 43300, Greece.
*Corresponding author: bilalisdimitrios@yahoo.gr

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Abstract

Organic cotton is a new industrial crop product. Field experiments were conducted to determine the effects of cultural systems and varieties on the growth, fiber quality and yield components of cotton crop (*Gossypium hirsutum* L.). The experiments, conducted during 2006 and 2007, were laid out in a split plot design with four replicates, two main plots (organic and conventional system) and two sub-plots (cotton varieties: Athena and Campo). There were no significant differences between the organic and conventional system for cotton growth, yield and fiber quality. The results suggest that the soil N released from both the inorganic ($80:40:40\,kg\,ha^{-1}$ $N:P_2O_5:K_2O$) and organic pool (green manure) were sufficient to maintain good growth. Inferior-quality fiber was produced in the variety. Campo, which had the lowest fiber fineness (micronaire), strength, length and reflection. In addition, this variety had the highest fiber elongation and yellowness. There were no significant differences between varieties as far as uniformity and leaf trash ratio are concerned. A positive correlation was observed between fiber strength and length. However, a negative correlation was found between lint yield and fiber strength.

Key words: organic cotton, green manure, vetch, fiber quality, lint yield, varieties

Introduction

Cotton (*Gossypium hirsutum* L.) is a major industrial crop in Greece[1], India[2], Turkey[3], USA[4], Pakistan[5] and Australia[6]. It is one of the most important fiber-producing plants; cotton and synthetic fibers meet most of the world's textile demand[3]. Both are associated with major environmental problems: synthetic fibers deplete fossil energy resources, while contemporary cotton cultivation is characterized by high water requirements and use of substantial amounts of fertilizers and pesticides[7].

Organic cotton grown by farmers worldwide increased by 152% during the 2007–2008 crop year. As a result, organic cotton production reached 145.872 metric tons (MT), equaling 668.581 bales, grown on 161,000 ha in 22 countries[8]. Turkey, India, China, Syria, Uganda, Tanzania, Israel, USA and Pakistan are the top ten organic cotton producing countries in the world, according to Organic Exchange. However, there are few references to organic cotton in the literature[2,9,10]. A niche market for organic cotton appears to already exist and is constantly growing. Agricultural production has become heavily reliant over the past 50 years on the use of synthetic fertilizers. This reliance on agrochemicals has resulted in the contamination of surface and ground water resources by nutrients in a number of different environments. About 25% of the world's insecticide use and more than 10% of the world's pesticide goes to cotton crops. In 2003, that amounted to about 55 million pounds of pesticides being sprayed on 12.8 million acres of cotton[8]. Management methods that decrease the requirement for agricultural chemicals are required to reduce adverse environmental impacts[11].

The use of green manure is one of the basic cultivation techniques of Organic Agriculture[12]. Legumes can be used as green manure thanks to their ability to fix atmospheric nitrogen. Vetch is a legume species well adapted to the soil

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and climate conditions of Greece. It can also be cultivated as plants for green manure, during the period between two major crops (intermediate crop) in the common rotation system of Greece[13], such as wheat/cotton, wheat/tobacco, etc. Vetch can be seeded at the beginning of October and then cut and incorporated into the soil at the end of April. Data obtained by other researchers[14–19] clearly demonstrate the beneficial effects of legumes on the yields of the following crops (cotton, wheat, barley, canola, maize, mustard and rice).

Organic cotton is grown using methods and materials that have a low impact on the environment. From an economic point of view, the organic cotton grown with the use of a cover crop either incorporated in the soil as green manure or even better, cut and sold as animal food for getting a second income, appears to be highly superior to conventional cotton growing, even when a flat price is taken into account[20]. In addition Swezey et al.[21] reported that cost of production per bale was on average 37% higher for organic than conventional cotton. This cost differential was due primarily to greater hand-weeding costs and significantly lower yields in organic cotton compared with conventional cotton. Organic cotton fiber is used in everything from personal care items, to home furnishings, children's products and clothes of all kinds and styles. In addition, organic cotton seed is used for animal feed, and organic cotton seed oil is used in a variety of food products. Organic cotton can also be presented as the solution to the current cotton market crisis, because its price can reach more than 20% above market[22].

The aim of this study was to determine the effects of (1) cultural system and (2) cotton varieties on plant growth and fiber quality of cotton crop. Variety selection, a key management component in any cropping system, is even more critical in organic cotton production. Moreover, while high yield potential is the predominant consideration, fiber properties are also major factors to be considered. Limited data are available regarding performance of varieties grown in an organic cropping system.

Material and Methods

Experimental design

A cotton crop (*G. hirsutum* L.) was established in the Karditsa (Central Greece), 304 km north of Athens. The soil was a clay loam (28.2% clay, 32.5% silt and 39.3% sand) with pH 7.11, organic matter 1.01%, electrical conductance (EC) 0.45 mS cm^{-1}, NO_3-N 16.3 mg kg^{-1} soil, P 15.8 mg kg^{-1} soil, K 257 mg kg^{-1} soil, Fe 77.4 mg kg^{-1} soil and Mg 1301 mg kg^{-1} soil. The experimental site has mild rainy winters and hot-dry summers. Some meteorological data of the experimental site are presented in Table 1. The experiment was set up on an area of 2496 m^2 according to the split plot design with four replicates, the two main plots (cultural systems: organic and conventional) and the two sub-plots (cotton varieties). The cotton cultivars were Athena and Campo. The sub-plot size was 10×8 m. According to soil analysis (NO_3-N 16.3 mg kg^{-1} soil, P 15.8 mg kg^{-1} soil and K 257 mg kg^{-1} soil), in the conventional plots, 400 kg ha^{-1} of fertilizer (20 : 10 : 10 kg ha^{-1} N : P_2O_5 : K_2O) was applied before sowing. In a clay loam soil, Girma et al.[23] have also reported a high lint yield with application of 90 : 20 : 75 kg ha^{-1} N : P : K. In organic plots, vetch crop as green manure was incorporated into the soil on 11 April 2006 and 2007. Vetch (*Vicia sativa* L. var Alexandros) was sown at the beginning of October 2006 and 2007 at a rate of 100 kg ha^{-1}. The amount of total N that accumulated on vetch plants in 2006 was 212 kg ha^{-1}, while in 2007 was 203 kg ha^{-1}.

Table 1. Meteorological data in experimental site during experimental period (May–September).

	May	June	July	August	September
2006					
Mean temperature (°C)	19.2	24.5	27.3	26.8	22.1
Mean relative humidity (%)	57.4	55.1	48.7	55.2	63.7
Precipitation (mm)	22	–	6	10	18
2007					
Mean temperature (°C)	18.6	25.9	26.1	27.7	23.6
Mean relative humidity (%)	59.0	54.3	51.8	49.2	61.2
Precipitation (mm)	31	10	9	4	7

Planting, irrigation, defoliation and weed control

Cotton was sown by hand in rows of 96 cm apart at a depth of 4 cm. Cotton was planted when soil temperature at a depth of 20 cm reached 15°C, at an approximate density of 156,000 plants ha^{-1}. The field was sown on 30 April 2006 and 2007 at a rate of 28 kg ha^{-1}. Plant emergence started 7 days after planting and was completed within 11 days after planting.

The irrigation was started in mid-June until 20 days before harvest; the field area was irrigated five times. A drip irrigation system was set up on the plots. The drip system consisted of laterals with 20 mm diameter with in-line drippers and at 0.40 m distance. The drippers had a discharge rate of 4 litres h^{-1} under an operation pressure of 1 atm. The total quantities of water were 203 and 224 mm for 2006 and 2007, respectively.

For defoliation on conventional plots pyraflufen-ethyl was used in the recommended dose 100 ml ha^{-1}.

Finally, weeds in organic plots, were controlled by hand, with two hoeings being carried out. This practice is one of the basic weed control methods of organic agriculture. Hand weed control resulted in an increase in the cost of production[21]. In addition, conventional plots received herbicide treatment: fluometuron 50% SC (Cotoran, 50 SC) at the recommended dose of 2.5 kg active ingredient ha^{-1}.

Table 2. Influence of cultural system (organic system: ORG, conventional system: CON) and cotton varieties (Athena and Campo) on dry weight of leaves (kg ha^{-1}), dry weight of stems (kg ha^{-1}), stem height (cm) and leaf area index (LAI) of cotton crop.

	Cultural system							
Varieties	**Dry weight of leaves**		**Dry weight of stems**		**Height**		**LAI**	
Experiment 2006	ORG	CON	ORG	CON	ORG	CON	ORG	CON
Athena	6834a	6769a	5056a	5187a	92.33a	89.67a	3.27a	2.98a
Campo	4878b	4766b	3879b	4123b	76.00b	80.67b	2.95a	2.76a
LSD_{system} ($P = 0.05$)	887 ($F = 0.67^{ns}$)		912 ($F = 1.61^{ns}$)		11.34 ($F = 1.02^{ns}$)		1.23 ($F = 0.34^{ns}$)	
$LSD_{varieties}$ ($P = 0.05$)	1145 ($F = 6.08$*)		803 ($F = 4.74$*)		7.89 ($F = 4.79$*)		0.51 ($F = 0.01^{ns}$)	
Experiment 2007	ORG	CON	ORG	CON	ORG	CON	ORG	CON
Athena	6649a	6663a	4931a	5263a	88.25a	90.00a	2.67a	2.79a
Campo	4577b	4931b	3992b	4150b	75.00b	84.25a	2.82a	2.03a
LSD_{system} ($P = 0.05$)	965 ($F = 0.15^{ns}$)		812 ($F = 1.35^{ns}$)		14.98 ($F = 0.88^{ns}$)		1.73 ($F = 0.78^{ns}$)	
$LSD_{varieties}$ ($P = 0.05$)	1328 ($F = 4.88$*)		864 ($F = 3.46$*)		8.16 ($F = 2.39^{ns}$)		0.82 ($F = 0.68^{ns}$)	

Means in each column followed by the same latter are not significantly different. The LSD ($P = 0.05$) for cultural systems and cotton varieties are also shown. *F*-test ratios are from ANOVA. Significant at *$P = 0.05$, ns: not significant.

Samplings, measurements and methods

Vegetative traits: plant height (cm), leaf area index (LAI), dry weight of leaves (kg ha^{-1}), dry weight of stems (kg ha^{-1}), 120 days after sowing (DAS). Yield and yield components: seed cotton yield (kg ha^{-1}), lint yield (kg ha^{-1}). Fiber quality: lint was analyzed for micronaire (fiber fineness), length (mm), strength (g tex^{-1}), uniformity ratio (%), reflectance (whiteness, %Rd), yellowness (+b), elongation (%) and leaf trash ratio (%).

For the computation of boll number, leaf area, dry weight of leaves, dry weight of stems and height, 10 plants were randomly selected from each plot. The dry weights of all plant parts were determined after drying for 48 h at 70°C. Leaf area was measured using an automatic leaf area meter (Delta-T Devices Ltd, Burwell, Cambridge, UK). Thus, the measurements of plant basis were converted into a LAI by multiplying by the average crop density of each plot.

The plants were harvested by hand twice. The first harvest took place when approximately 60% of the bolls opened at the end of September. The second harvest followed in the middle of October, approximately 3 weeks after the first. The cotton seed yield was also determined by manually harvesting the open bolls of the cotton plants in the two center rows of each plot.

The High Volume Instrument spectrum (by Zellweger Uster Inc., Uster, Switzerland) system was used to determine lint quality:

1. The fiber length in millimeters was measured as 2.5% span length.
2. The fiber uniformity was determined as the ratio of the mean length to the upper-half mean length expressed as a percentage.
3. The fiber strength was determined as the force (g tex^{-1}) necessary to break the fiber bundle.
4. The micronaire reading was taken as the fineness of the fiber expressed in standard micronaire units.
5. The whiteness was expressed as percentage reflectance (%Rd), and the yellowness (+b) represented the degree of cotton pigmentation.

Statistical analysis

For calculating analysis of variance and comparisons of means the software Statsoft[24] was used. The LSD test was used to detect and separate the mean treatment differences. Regression and correlation analyses were used to describe the relationships between growth parameters and fiber characteristics. All comparisons were made at the 5% level of significance.

Results and Discussion

Cotton growth and yield

The variety selected determines cotton growth and lint yield[1,25]. The lowest dry weight of stems and leaves was found in Campo variety (Table 2). There were statistically significant differences between Campo and Athena varieties. Similar results were observed for both years (2006 and 2007). Moreover, concerning the LAI (Table 2), there were no statistically significant differences between the Athena and Campo varieties under the two cultural systems. The lowest height of stems was found in Campo variety (75 and 76 cm for organic and 80.67 and 84.25 cm for conventional in 2006 and 2007, respectively). Hcritholt et al.[26] found that modern and obsolete varieties had similar LAI responses to N in early and mid season but by late season, LAI of modern varieties were greater under high N than were those for the obsolete cultivars. Moreover the highest seed cotton yields were found in the Campo variety (under organic: 4743 and 4327 kg ha^{-1} for Campo and Athena, respectively, for 2006; and 4612 and 4503 kg ha^{-1} for Campo and Athena, respectively, for 2007, Table 3). Similar results were observed for the conventional system.

Table 3. Seed cotton yield (kg ha^{-1}) and lint yield (kg ha^{-1}) for cotton varieties (Athena and Campo) as influenced by organic (ORG) and conventional cultivation system (CON).

	Cultural system			
Varieties	**Seed cotton yield**		**Lint yield**	
Experiment 2006	ORG	CON	ORG	CON
Athena	4327a	4543a	958a	976a
Campo	4743b	4876b	1033b	1078b
LSD_{system} ($P = 0.05$)	1032 ($F = 0.22^{ns}$)		45.76 ($F = 1.01^{ns}$)	
$LSD_{varieties}$ ($P = 0.05$)	280 ($F = 5.21$*)		30.05 ($F = 5.67$*)	
Experiment 2007	ORG	CON	ORG	CON
Athena	4503a	4374a	851a	878a
Campo	4612a	5153b	886b	884a
LSD_{system} ($P = 0.05$)	1239 ($F = 0.01^{ns}$)		131.3 ($F = 0.01^{ns}$)	
$LSD_{varieties}$ ($P = 0.05$)	410 ($F = 2.24^{ns}$)		29.78 ($F = 4.78$*)	

Means in each column followed by the same latter are not significantly different. The LSD ($P = 0.05$) for cultural systems and cotton varieties are also shown. F-test ratios are from ANOVA. Significant at *$P = 0.05$, ns: not significant.

The highest lint yields were found in the Campo variety (under organic: 1033 and 958 kg ha^{-1} for Campo and Athena, respectively, for 2006; and 886 and 851 kg ha^{-1} for Campo and Athena, respectively, for 2007, Table 3). Similar results were observed for the conventional system.

There were statistically significant differences in yields between Campo and Athena varieties in all cases ($F = 5.67$, $P < 0.05$ and $F = 4.78$, $P < 0.05$, for 2006 and 2007, respectively), except under the conventional cultural system in 2007 (Table 3).

In contrast, there were no significant differences between the organic and conventional cultural system with regard to cotton growth and lint yield (Tables 2 and 3). Nor was any cultural system × varieties interaction found.

The results suggest that the soil N released from both inorganic (80 : 40 : 40 kg ha^{-1} N : P_2O_5 : K_2O) and organic pool (green manure) was sufficient to maintain good growth. The amount of total N that accumulated in vetch plants and was incorporated into the soil in 2006 was 212 kg ha^{-1}, while in 2007 it was 203 kg ha^{-1}. Girma et al.[23] reported that cotton varieties attained maximum lint yield with the application of 135 : 30 : 75 kg ha^{-1} N : P_2O_5 : K_2O. Also, Pettigrew et al.[27] observed that the application of 112 kg ha^{-1} K did not increase lint yield in eight out of nine genotypes. In addition Gormus[28] reported that the application of 160 kg ha^{-1} K_2O produced significant differences in seed cotton yield, lint yield and boll weight compared with untreated control.

Data obtained by other researchers clearly demonstrated the beneficial effects of organic fertilization on cotton growth and yield. Blaise[2] reported that seed cotton yield in organic plots was significantly greater than in plots under modern methods of cultivation. Also, Thomopoulos et al.[10] reported that higher seed cotton yield was found in the plots where vetch had been incorporated. Blaise et al.[29] have also found that seed cotton yield was improved with the addition of farmyard manure. Moreover, Parvez et al.[5] reported that cotton crops grown in organic fertilizer harbor a lower number of insect pests. In addition, Swezey et al.[21] found that average 6-year yields were 4.4, 5.4 and 6.7 bales ha^{-1} for organic, integrated pest management and conventional treatments, respectively.

Data obtained by other researchers clearly demonstrated the beneficial effects of green manuring on the yields of the following crops. Karkanis et al.[17] found that green manures (vetch and red clover) affected tobacco growth. Previous studies have also shown the benefits of green manures on root growth[11,19]. In cotton, Thomopoulos et al.[10] reported that the higher values of the root characteristics (dry weight, length density, diameter and surface area) of the cotton were found in the plots where vetch had been incorporated. The favorable effect of green manures on root growth was likely due to increase in organic matter, which led to better physical (bulk density and soil aggregation) and chemical conditions (total soil nitrogen)[19,30]. Moreover, Mygdakos et al.[20] observed that seed cotton yield of the treatment with legumes incorporation was higher (3780 kg ha^{-1}) than the conventional treatment (3617 kg ha^{-1}).

Maintaining and improving soil quality is crucial if agricultural productivity and environmental quality are to be sustained for future generations.

Fiber quality

The lowest fiber strength was found in Campo variety (under organic: 28.33 and 30.21 g tex^{-1} for Campo and Athena, respectively, for 2006; and 28.62 and 30.58 g tex^{-1} for Campo and Athena, respectively, for 2007, Table 4). There were statistically differences between Campo and Athena varieties ($F = 11.22$, $P < 0.001$ and $F = 9.16$, $P < 0.001$, for 2006 and 2007, respectively). However, there were no significant differences between the organic and conventional cultural systems ($F = 0.01^{ns}$ and $F = 0.05^{ns}$ for 2006 and 2007, respectively). Moreover, concerning the micronaire, fiber length and uniformity ratio (Table 4), there were no significant differences between the organic and conventional cultural system, or between the Athena and Campo varieties.

The lowest fiber elongation was found in the Campo variety (under organic: 6.67 and 5.02% for Campo and Athena, respectively, for 2006; and 6.86 and 4.68% for Campo and Athena, respectively, for 2007, Table 5). These differences were statistically significant ($F = 14.45$, $P < 0.001$ and $F = 17.60$, $P < 0.001$ for 2006 and 2007, respectively). In contrast, there were no significant differences between the organic and conventional cultural systems.

There were statistically significant differences in lint reflectance between Campo and Athena varieties ($F = 4.01$, $P < 0.05$ and $F = 3.33$, $P < 0.05$ for 2006 and 2007, respectively). The lint reflectance was lower in the Campo variety (under organic: 81.78 and 83.36%Rd for Campo and Athena, respectively, for 2006; and 81.42 and

Table 4. Effects of cropping system (organic: ORG and conventional: CON) and cotton varieties (Athena and Campo) on fiber fineness (micronaire), fiber strength (g tex^{-1}), fiber length (mm) and uniformity ratio (%) of cotton lint.

	Cultural system							
Varieties	**Fiber fineness**		**Fiber strength**		**Fiber length**		**Uniformity ratio**	
Experiment 2006	ORG	CON	ORG	CON	ORG	CON	ORG	CON
Athena	3.69a	3.71a	30.21a	30.12a	29.09a	29.05a	85.12a	84.76a
Campo	3.61a	3.64a	28.33b	28.75b	29.02a	28.97a	84.96a	84.81a
LSD_{system} ($P = 0.05$)	0.31 ($F = 0.04^{ns}$)		0.34 ($F = 0.01^{ns}$)		0.79 ($F = 0.01^{ns}$)		2.11 ($F = 0.14^{ns}$)	
$LSD_{varieties}$ ($P = 0.05$)	0.23 ($F = 0.05^{ns}$)		1.02 ($F = 11.22$***)		0.63 ($F = 0.32^{ns}$)		1.32 ($F = 0.21^{ns}$)	
Experiment 2007	ORG	CON	ORG	CON	ORG	CON	ORG	CON
Athena	3.79a	3.75a	30.58a	30.72a	29.02a	28.95a	84.83a	84.33a
Campo	3.56a	3.67a	28.62b	28.55b	28.91a	28.94a	84.72a	84.72a
LSD_{system} ($P = 0.05$)	0.61 ($F = 0.14^{ns}$)		1.12 ($F = 0.05^{ns}$)		0.45 ($F = 0.14^{ns}$)		1.53 ($F = 0.08^{ns}$)	
$LSD_{varieties}$ ($P = 0.05$)	0.46 ($F = 0.39^{ns}$)		1.21 ($F = 9.16$***)		0.54 ($F = 0.82^{ns}$)		1.50 ($F = 0.38^{ns}$)	

Means in each column followed by the same latter are not significantly different. The LSD ($P = 0.05$) for cultural systems and cotton varieties are also shown. *F*-test ratios are from ANOVA. Significant at ***$P = 0.001$, respectively, ns: not significant.

Table 5. Effects of cotton varieties (Athena and Campo) on fiber quality (reflectance (%Rd), yellowness (+b), fiber elongation (%) and leaf trash ratio (%)) under two cultural systems (organic: ORG and conventional: CON) in 2006 and 2007.

	Cultural system							
Varieties	**Reflectance**		**Yellowness**		**Fiber elongation**		**Leaf trash ratio**	
Experiment 2006	ORG	CON	ORG	CON	ORG	CON	ORG	CON
Athena	83.36a	83.51a	7.71a	7.56a	5.02a	4.96a	5.66a	5.74a
Campo	81.78b	82.07b	8.11b	8.16b	6.67b	6.75b	6.32a	6.10a
LSD_{system} ($P = 0.05$)	1.04 ($F = 0.01^{ns}$)		0.21 ($F = 0.71^{ns}$)		1.31 ($F = 0.12^{ns}$)		2.76 ($F = 0.04^{ns}$)	
$LSD_{varieties}$ ($P = 0.05$)	1.21 ($F = 4.01$*)		0.6 ($F = 8.07$**)		1.05 ($F = 14.45$***)		1.37 ($F = 0.84^{ns}$)	
Experiment 2007	ORG	CON	ORG	CON	ORG	CON	ORG	CON
Athena	82.50a	83.93a	7.52a	7.67a	4.68a	4.88a	5.75a	5.87a
Campo	81.42b	81.91b	8.23b	8.26b	6.86b	6.60b	6.50a	6.62a
LSD_{system} ($P = 0.05$)	0.95 ($F = 0.01^{ns}$)		0.15 ($F = 0.65^{ns}$)		1.01($F = 0.30^{ns}$)		1.39 ($F = 0.44^{ns}$)	
$LSD_{varieties}$ ($P = 0.05$)	0.92 ($F = 3.33$*)		0.36 ($F = 7.72$**)		0.73 ($F = 17.60$***)		2.37 ($F = 0.46^{ns}$)	

Means in each column followed by the same latter are not significantly different. The LSD ($P = 0.05$) for cultural systems and cotton varieties are also shown. *F*-test ratios are from ANOVA. Significant at *$P = 0.05$, **$P = 0.01$ and ***$P = 0.001$, respectively, ns: not significant.

82.50%Rd for Campo and Athena, respectively, for 2007, Table 5). In addition, there were no significant differences between the organic and conventional cultural systems.

The highest lint yellowness (+b) was found in the Campo variety (under organic: 8.11 and 7.71 +b for Campo and Athena, respectively, for 2006; and 8.23 and 7.52 +b for Campo and Athena, respectively, for 2007; under conventional: 8.16 and 7.56 +b for Campo and Athena, respectively, for 2006; and 8.26 and 7.67 +b for Campo and Athena, respectively, for 2007, Table 5). These differences were statistically significant ($F = 8.07$, $P < 0.01$ and $F = 7.72$, $P < 0.01$ for 2006 and 2007, respectively). In contrast, there were no significant differences between the organic and conventional cultural systems.

Moreover, concerning the leaf trash ratio there were no significant differences between the organic and conventional cultural systems, or between the Athena and Campo varieties. Finally, in these fiber traits, no cultural × variety interaction was found.

Our results indicate that there were no significant differences between the organic and conventional cultural systems for fiber properties. The results suggest that the soil N released from both inorganic and organic pool was sufficient to maintain good fiber quality. The amount of total organic N incorporated into the soil in 2006 was 212 kg ha^{-1}, while in 2007 it was 203 kg ha^{-1}. Girma et al.[23] reported that N rates greater than 90 kg ha^{-1} significantly reduce lint quality variables. This response is in contrast to the result of Attia et al.[31], who found that the lowest values of fiber length, micronaire and uniformity ratio were obtained from plots that received organic fertilizer alone. Also, Pettigrew et al.[27] observed that the application of 112 kg ha^{-1} K had a positive effect on lint quality. Blaise[2] found that the cotton grown under organic conditions as compared with the modern method of cultivation had significantly better fiber length (25.1 and 24.00 mm, respectively) and strength (18.8 and 17.9 g tex^{-1}). Also, Blaise et al.[29] reported that uniformity ratio and per cent lint in the seed cotton was greater in farmyard

Table 6. Correlation coefficients[1] between plant-lint parameters of cotton.

	F.L.	F.S.	E.	U.	Y.	R.	M.	DWL	LAI	L.Y	S.C.Y
Fiber length (F.L.)	–	0.71***	−0.45*	0.76***	ns	−0.46*	ns	ns	ns	−0.48*	ns
Fiber strength (F.S.)		–	−0.72***	0.44*	ns	ns	ns	ns	ns	−0.60***	ns
Elongation (E.)			–	ns	ns	ns	ns	ns	ns	ns	ns
Uniformity (U.)				–	0.71***	ns	ns	ns	ns	ns	ns
Yellowness (Y.)					–	−0.53**	ns	ns	ns	ns	ns
Reflectance (R)						–	ns	ns	ns	ns	ns
Micronaire (M)							–	ns	ns	−0.44*	0.49*
Dry weight of leaves (DWL)								–	0.86***	ns	0.45*
LAI									–	ns	0.50*
Lint yield (L.Y.)										–	ns
Seed cotton yield (S.C.Y.)											–

[1] r was calculated using the linear equation. Significant at $*P = 0.05$, $**P = 0.01$ and $***P = 0.001$, respectively. ns: not significant.

manure plots than in the plots without manure. Moreover, Bilalis et al.[11] have also reported high quality (nicotine content) of a tobacco crop under organic fertilization.

Our results indicate that fiber fineness (micronaire) did not differ between the two varieties tested. Fiber fineness ranged from 3.56 micronaire for the Campo variety to 3.79 micronaire for the Athena variety. There were no significant differences between varieties for fiber length and uniformity ratio. In addition, concerning the fiber strength, the difference between varieties was significant. This trait ranged from 28.55 to 30.81 g tex^{-1}. The strongest fibers were obtained from Athena (30.72 g tex^{-1}).

Fiber strength depends on many factors, with genotype being the most important. Cultivar selection and cultural practices determine fiber property levels. The variety cultivated determines the genetic background for fiber length and strength[4]. Growing conditions will affect the expression of the genetic potential. Moreover, fiber strength is more responsive to the growth environment than is fiber length[1]. Hulugalle et al.[6] observed that a change in fiber quality is a consequence of soil and environmental changes. Blaise et al.[29] reported inferior fiber quality because of delayed planting and early cessation of rain. Less than normal rainfall caused the crop to experience moisture stress during fiber elongation. Also, water stress occurring during the cotton growing season may reduce lint yield and quality. Moreover, Dagdelen et al.[32] found that fiber quality was significantly affected by drip application rate or water stress. Fiber length and strength generally decreased as water deficit levels increased.

The differences between varieties for yellowness and reflectance (whiteness) were significant. The highest fiber yellowness was found in Campo variety; additionally, the lowest fiber reflectance was also found in Campo variety. Nichols et al.[4] reported that differences in color measurements due to cultivar were not consistent. The difference between varieties for fiber elongation was significant. Athena variety with a mean of 4.76% had the least elastic fibers, while the Campo variety had the most elastic fibers with a mean of 6.73%. In contrast the differences between varieties for leaf trash ratio were not significant. Wrather et al.[33] reported that planting dates significantly affected fiber quality: lint yellowness and leaf trash varied among planting dates and they were greater for the last date than all other planting dates. Discolored cotton is generally associated with weathering[34].

Correlations between yield, yield components and fiber properties

Correlation coefficients among traits are given in Table 6. Plant height correlated with dry weight of shoots and LAI ($r = 0.84***$, $P < 0.001$ and $r = 0.67***$, $P < 0.001$ respectively). Seed cotton yield had positive and significant correlation with LAI and dry weight of shoots ($r = 0.50*$, $P < 0.05$ and $r = 0.47*$, $P < 0.05$, respectively).

In this work, cumulative data showed that Campo, the most productive cultivar, had significantly lower relative fiber strength (Table 4), suggesting a negative correlation (Table 6) between these two characteristics. Smith and Coyle[35] reported that fiber strength and length were negatively associated with the most basic within-boll lint yield components. Lint yield correlated negatively and significant with fiber strength ($r = -0.60***$, $P < 0.001$). Similar results were obtained by other researchers[36]. Moreover, seed cotton yield had strongly positive and significant correlations with fiber fineness (micronaire). Lint percentage had both a positive and significant correlation with fiber elongation but a negative and significant correlation with fiber fineness.

The multiple regression analysis indicates that there was a statistically significant relationship between fiber strength (S), elongation (E) and lint yield (Y):

$$\text{Fibre strength } (S) = 49.88 - 0.834 \text{ elongation} - 0.09 \text{ lint yield}$$

St. Error: (4.31) (0.17) (0.02) $R^2_{(\text{adjust})} = 66.59\%$

P-level: (0.0001) (0.0001) (0.002)

The R^2 statistic indicates that this model explains 67% of the variability in fiber strength.

Fiber strength was positively correlated with fiber length and uniformity ratio ($r = 0.71$***, $P < 0.001$ and $r = 0.44$*, $P < 0.05$, respectively), a result expected, as both traits have a close connection with fiber perimeter. Perimeter had the greatest effect on micronaire (76.5% of total sums of squares), but also affected more than 35% of the variation in models explaining length and strength[37]. Other investigators reported that fiber strength and length were positively associated[1]. There was a negative correlation between fiber strength and fiber elongation. As the yield increased, the strength was reduced. The correlation was negative and significant between fiber strength and fiber elongation. Finally, fiber yellowness had a strongly negative correlation with fiber reflectance (whiteness).

Conclusions

Our results indicate that there were no significant differences between the organic and conventional cotton for cotton growth, yield and fiber quality. The variety Campo had the lowest fiber fineness (micronaire), strength, length and reflectance. In addition, Campo variety had the highest fiber elongation and yellowness. Also, there were no significant differences between cultivars for uniformity and leaf trash ratio. Positive correlation was observed between fiber strength and length. Finally, negative correlation was found between lint yield and fiber strength. Concerning the organic agriculture system, green manure can affect cotton growth.

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Effects of Fair Trade and organic certifications on small-scale coffee farmer households in Central America and Mexico

V. Ernesto Méndez[1,*], Christopher M. Bacon[2], Meryl Olson[3], Seth Petchers[4], Doribel Herrador[5], Cecilia Carranza[6], Laura Trujillo[7], Carlos Guadarrama-Zugasti[7], Antonio Cordón[8], and Angel Mendoza[8]

[1]Environmental Program and Department of Plant and Soil Science, The University of Vermont, 153 So. Prospect St., Burlington, VT 05401, USA
[2]Department of Geography, 513 McCone Hall, University of California-Berkeley, Berkeley, CA 94720-4740, USA
[3]Department of Plant and Soil Science, Hills Agricultural Bldg, 105 Carrigan Drive, The University of Vermont, Burlington, VT 05405, USA
[4]1 South Ivy Street, Denver, CO 80224, USA
[5]University of Barcelona, Calle Balmes 17-2a-2, Terrassa 08225, Barcelona, Spain
[6]Ministerio de Medio Ambiente y Recursos Naturales, Unidad de Planificación—Area de Economía Ambiental, Carretera a Santa Tecla Km. 5 1/2, Calle y Colonia Las Mercedes, Edificio MARN, San Salvador, El Salvador
[7]Universidad Autonoma de Chapingo, CRUO, Km. 3 Carretera Huatusco-Jalapa, Huatusco, Veracruz, Mexico
[8]Asociación CRECER, 20 Calle 14-19 zona 10, Guatemala Ciudad, Guatemala
*Corresponding author: emendez@uvm.edu

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Abstract

We provide a review of sustainable coffee certifications and results from a quantitative analysis of the effects of Fair Trade, organic and combined Fair Trade/organic certifications on the livelihood strategies of 469 households and 18 cooperatives of Central America and Mexico. Certified households were also compared with a non-certified group in each country. To analyze the differences in coffee price, volume, gross revenue and education between certifications, we used the Kruskal–Wallis (K–W) non-parametric test and the Mann–Whitney *U* non-parametric test as a *post-hoc* procedure. Household savings, credit, food security and incidence of migration were analyzed through Pearson's chi-square test. Our study corroborated the conditions of economic poverty among small-scale coffee farmer households in Central America and Mexico. All certifications provided a higher price per pound and higher gross coffee revenue than non-certified coffee. However, the average volumes of coffee sold by individual households were low, and many certified farmers did not sell their entire production at certified prices. Certifications did not have a discernable effect on other livelihood-related variables, such as education, and incidence of migration at the household level, although they had a positive influence on savings and credit. Sales to certified markets offer farmers and cooperatives better prices, but the contribution derived from these premiums has limited effects on household livelihoods. This demonstrates that certifications will not single-handedly bring significant poverty alleviation to most coffee-farming families. Although certified coffee markets alone will not resolve the livelihood challenges faced by smallholder households, they could still contribute to broad-based sustainable livelihoods, rural development and conservation processes in coffee regions. This can be done by developing more active partnerships between farmers, cooperatives, certifications and environmental and rural development organizations and researchers in coffee regions. Certifications, especially Fair Trade/organic, have proven effective in supporting capacity building and in serving as networks that leverage global development funding for small-scale coffee-producing households.

Key words: farmer cooperatives, political ecology, rural livelihoods, coffee crisis, alternative markets, sustainable coffee

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Introduction

The coffee price crisis starting in the early 1990s, and deepening between 1999 and 2003, had enormous social and economic impacts on coffee producers around the world[1,2]. Between 1989 and 2004, green coffee prices fell from US$1.20 lb^{-1} to between US$0.45 lb^{-1} and US$0.65 lb^{-1}. Although prices have rebounded to levels consistent with the market averages during the previous 50 years (generally between US$1.00 lb^{-1} and US$1.25 lb^{-1})[3], the consequences of the price crash, and the chronic poverty that already existed, remain. In other words, even though prices have recovered, the coffee crisis continues[4,5].

In the midst of this situation, great expectations were placed on the role of several 'sustainable coffee' certification initiatives, as key alternatives for farmers to confront the crisis[6]. Certification systems claim to offer a combination of benefits including higher and more stable prices to farmers, and increased market access and technical assistance. In turn, farmers and their organizations must meet standards and subject themselves to inspections. As the number of certification initiatives increases, and consumers become more aware of different certification options, there is a growing concern to accurately document the real impact of these alternatives on coffee producers and their families. Recent research on sustainable coffee certification points to differentiated impacts on growers for each type of certification[7,8]. These studies provide important comparative examinations of certification standards and practices, often focusing on the macro-impacts of each program. However, most lack household- and community-level data that document the perceived benefits and limitations, as expressed by growers and their families[9].

The general objective of this research was to analyze the effects of Fair Trade and organic certifications on the livelihoods of coffee producer households of Central America and Mexico. Our specific objectives were: (1) to provide a critical review of the different types of sustainable coffee certifications; (2) to analyze the effects of Fair Trade, organic and combined Fair Trade/organic certifications on the livelihood strategies of coffee-producing households in Central America (El Salvador, Guatemala and Nicaragua) and Mexico, including social (e.g., social networks) and economic (e.g., gross coffee revenue) variables. This information was used to discuss the current and potential benefits and limitations of these certifications as a means to support the livelihoods of coffee-producing households.

Review of Sustainable Certification Initiatives

The rise of specialty coffee and sustainability certifications

The Specialty Coffee Association of America (SCAA) defines specialty coffee as follows: 'Sometimes called "gourmet" or "premium" coffee, specialty coffees are made from exceptional beans grown only in ideal coffee-producing climates. They tend to feature distinctive flavors, which are shaped by the unique characteristics of the soil that produces them'[10]. Under the specialty coffee umbrella, certified coffees are those which receive a certificate or label from a third-party, independent agency[11], such as certified Fair Trade (e.g., FLO label) or certified organic (e.g., USDA or Naturland labels). 'Sustainable coffee certification' is an umbrella term encompassing several types of certifications, and combinations of certifications that explicitly address social and environmental concerns and standards. Specialty and sustainable coffee markets have expanded rapidly with increased consumer awareness regarding issues of quality, social equity, taste, health and environment[12,13]. These trends are evident in the expanding retail market values for the specialty coffee market segment, which has increased from less than $4 billion in the early 1990s to over $11 billion in 2006[14]. As of 2004, about 10% of global coffee exports could be considered specialty coffee, and of these an estimated 20% (or 2% of the global supply) carried some type of certification (Table 1). The percentage of specialty and sustainable coffees exported from Central America is significantly above the global average. During the 2002/2003 harvest, an estimated 6% of the region's total exports were sold into organic (1.5%), Fair Trade (3.6%) and Rainforest Alliance (0.75%) certifications[15]. Although small, this certified market segment continues to grow rapidly, with annual rates ranging from 10 to over 30%, depending on the year and the certification program[6,16]. If we expand the 2002/2003 market figures to include Mexico, account for the rapid growth rates among these certification programs and document the presence of newer sustainable coffee certification programs (e.g., Utz certified and Starbucks CAFE Practices), as of 2003/2004, these certified coffees accounted for 8–13% of the region's coffee production.

Certified organic coffee

Organic certification addresses standards that regulate the coffee *production process*. Although there are variations between certifiers, most organic standards include the following: 'ecological' management of farms; soil conservation practices; abstention from the use of synthetic fertilizers, pesticides and genetically modified crops; and intensive on-farm record keeping[8,17,18]. Organic certification also establishes a separate chain of custody ensuring that certified organic food is separated from conventional products in any processing stages.

Organic agriculture has grown quickly in Latin American, expanding from almost 4.9 million ha of certified organic land in 1998, to 5.8 million ha by 2004[19,20]. Expanded production is associated with increasing demand in northern markets, including a 20% growth rate in the volume of organic coffee imports to the USA, since 2004[16]. In 2002/2003, more than 2% of the coffee lands in Central

Table 1. Differentiated and certified coffee in relation to total volumes sold worldwide (2003–2004).

Market segment	Volume (metric tons)	% of total	Source
Conventionally traded coffee	4,659,522	90.70	This table
Estimated exported volume of differentiated coffee	480,000	9.30	Lewin et al.[2]
Total green coffee exported	5,139,522	100	ICO[3]
Certified coffee exports organic	26,400	0.51	Ponte[7]
Fair Trade (of which 14,642 is also organic)	28,283	0.55	TransFair USA[22]
Shade grown	660	0.01	Ponte[7]
Rainforest alliance	10,000	0.19	Courville[11]
Utz Kapeh	14,000	0.27	Courville[11]
Estimated total certified coffee (13.7% of differentiated coffee is also certified)	65,702	1.28	This table

Most data refer to 2003. Fair Trade lb, converted to metric tons based on 2.2 lb = 1 kg; 1000 kg = 1 metric ton. Data from TransFair reported originally by FLO. The organic and shade grown data are from Ponte[7] and Fair Trade data are from this table. The estimated 10% growth rate is taken from Ponte[7]. While Ponte considered the overlap between total fair trade production and the 52% that is also certified organic, this summary assumes that the organic total estimated by Ponte excludes the Fair Trade organic coffee. This table is a new estimate addressing the segments in the global coffee trade as of 2003. According to Raynolds et al.[8], Utz Kapeh, Rainforest Alliance and Bird Friendly certified farms have all have substantially increased their production by 2004; however, these three certifications systems report the total volumes of coffee produced on certified farms although much of this coffee is still exported as conventional coffee and not necessarily purchased under these terms (see Table 3 in Raynolds et al.[8]).

America were certified organic, with higher percentages in Nicaragua and Guatemala[21]. Organic coffee does not establish a minimum price paid to producers or exporters, but sets a premium above that established by the New York Board of Trade. In 2002/2003, a survey of importers reported that organic coffee price premiums in Guatemala averaged an estimated \$0.40 lb^{-1} above the market, and in Nicaragua and El Salvador they were \$0.25 lb^{-1} and \$0.30 lb^{-1}, respectively[21]. Globally, an estimated 52% of the coffee produced by certified Fair Trade cooperatives is also organic[22].

Fair Trade

In contrast to organic, Fair Trade certification specifically focuses on smallholder producer organizations, and the relations, prices and standards associated with the trade process[23]. Fair Trade advocates believe that fairer trade can lead to individual and collective empowerment if it follows standards and enforcement mechanisms that support human rights, dignity and sustainable development[24]. 'Empowerment' can be referred to as the ability of individuals and/or groups to act on their own in order to achieve their self-defined goals[25]. Fair Trade originated as a solidarity movement that supported partnerships between northern social justice advocates and impoverished southern producers[5,6]. After these initiatives saw significant growth in the 1980s, leaders in the movement decided to establish standards and certification mechanisms that would allow them to expand the volumes of fairly traded goods. These efforts were consolidated in the early 21st century, when the Fair Trade Labeling Organization (FLO) was established[5]. FLO establishes standards and certifies producers, organizations and traders that pay minimum prices; provides a price premium for social development; trades directly with smallholder coffee organizations; signs contracts that encourage long-term planning and stability; and provides up to 60% of pre-harvest credit when requested[26].

Although low international coffee prices motivated many farmers and roasters to seek Fair Trade certification, supply continues to outpace demand, and only 20–25% of Fair Trade certified coffee receives a premium. Recently, the USA, a latecomer to Fair Trade certification, has posted exponential growth rates[7]. The USA is now the largest Fair Trade certified coffee market in the world (almost 24,000 metric tons per year in 2006), even though this only amounts to 3% of the entirety of the US market[27]. According to TransFair USA, since 1998 74.3 million lb of Fair Trade certified coffee have been sold, and these sales have contributed to a cumulative total of \$60.4 million in price premiums above conventional coffee prices[22].

Bird Friendly, Rainforest Alliance and Utz certified coffees

Shade coffee certifications seek to reward coffee growers that manage their plantations in a way that supports the conservation of tropical species and habitats, with an emphasis on maintaining a diversified shade tree canopy (instead of managing 'full sun' plantations that have no shade trees)[28–31]. Shade coffee certifications have struggled to compete with other labels, and continue to account for market segments smaller than Fair Trade or organic[7,32]. The dominant labels for shade certification have been The Rainforest Alliance (RA) label and Smithsonian Migratory Bird Center's Bird Friendly™ coffee. Smithsonian also requires organic certification, which might result in higher ecological standards than RA[33–35].

RA's certification standards include using minimum levels of native shade tree biodiversity, limiting the use of highly toxic agro-chemicals, maintaining a healthy working and living environment for workers and enforcing national labor laws[36]. Critics of RA claim that environmental standards are lower than those required by certified organic coffee and that social development criteria are below the social objectives of Fair Trade[37].

Utz certified (formerly Utz Kapeh) was launched in 1997 by Royal Ahold, a Netherlands-based supermarket company. It seeks to integrate improved agricultural practices through the 'Euro-Retailer Produce Working Group-Good Agricultural Practices' (EUREP-GAP) with Social Accountability International's (SAI) 8000 social condition guidelines. EUREP-GAP certifies farms for 'good agricultural practices'[38], whereas SAI offers a certification to ensure adequate working conditions for laborers[39]. The initial certification criteria were developed in collaboration with a number of large coffee estates in Guatemala[36]. According to its representative in Guatemala, interviewed in 2004, Utz certified saw a tenfold increase in global sales, from 2000 certified tons of coffee in 2002 to 21,000 tons in 2004.

Assessing the effects of sustainable coffee certification

Several macro-level studies have described sustainable coffee certifications[7,8,36] and documented premiums where certified producers received between US$0.05 lb^{-1} and US$0.50 lb^{-1} above non-certified growers[21]. Other scholars have developed empirically rich ethnographic studies on how international certification systems are translated into the daily lives of small-scale farmer communities and cultures[40–45]. Most of this research agrees that higher prices, training and more connections to international networks are some of the advantages for farmers and cooperatives that sell to Fair Trade and organic markets[37,41,42,46]. Some of the disadvantages include high costs of certification; additional labor investments and lower yields for organic production; the need for increasingly sophisticated record keeping; higher quality standards; and the purchase and payment of certified coffee later in the season[6,41,47]. Conventional coffee, which refers to all non-certified forms of coffee production and trade, is generally sold faster and with far fewer quality requirements[23]. Several studies have documented the economic (e.g., higher prices and financing) and social (e.g., links to support networks and social investment) benefits of Fair Trade to farmer cooperatives[9], but only a few have analyzed these issues at the household level in an international comparative study (but see Jaffee[41] and Arnould et al.[48]).

Research Approach and Methods

Of particular importance to our research was to develop a better understanding of the current livelihood strategies of small-scale coffee farming households and how these are affected by certified coffee markets. The concept of livelihoods, which has been extensively applied in development studies[49], can be defined as 'comprising people, their capabilities and their means of living (e.g., food, income and assets)'[50], and how they make this living meaningful[51]. Our analysis was guided by a political ecology approach, with a focus on rural livelihoods. Political ecological perspectives have focused on livelihoods to analyze the social reproduction of farmer communities in developing countries, and how these are affected by social and ecological processes associated with natural resources access, governance and management[52–54]. Although political ecology argues for the need to examine social and ecological processes across multiple geographic scales (e.g., local, national and global)[55–58], this paper focused mainly on the household and community levels (local/regional). However, our research does address several points of interaction at broader scales, primarily through our discussion of second- and third-level cooperative organizations in different countries, and their international social networks. Our findings also provide insights into the local- and regional-level responses of households and cooperatives to globally driven events, such as the international coffee price crisis[23].

Furthermore, our analysis of household livelihood strategies and their relationship to the coffee commodity chain connects our research to debates on the governance of global value chains[59,60]. An in-depth examination of coffee household livelihood conditions and strategies, as well as their relationship to cooperatives, complements the global value chain literature on coffee. With a few notable exceptions (see Daviron and Ponte[61]), this body of work has focused primarily on regulations, value-added strategies and rent appropriations[62–64]. This paper contributes an in-depth assessment of locally situated social and economic impacts resulting from participation in certified or conventional coffee value chains. Although a deeper discussion of our results, in terms of global value chain analysis, is beyond the scope of this paper, we believe that our findings will inform future examinations of livelihood outcomes associated with the producer end of the value chain.

Research design and methods

Field surveys were conducted between November 2004 and December 2005, providing data for the 2003/2004 coffee harvest. In each country we worked with researcher teams that were based in-country. Two methodological workshops were held previous to field research to develop standardized data collection protocols. Countries, team members and cooperatives were chosen based on previous collaborative history among researchers, a team's established relationship with coffee farmers and cooperatives, and a cooperative's willingness to participate.

Our research design was a stratified survey, with country and certification type as main strata. We chose

Table 2. Number of cases and sample sizes for household surveys per certification type and country.

Country	Certification	Number of cases	Number of household surveys	Mean area under coffee cultivation (ha)[1]	Mean coffee yield
Guatemala	Non-certified	1 cooperative	30	2.1	703
	Fair Trade	1 cooperative	30	1.3	960
	Fair Trade and organic	2 cooperatives	60	1.4	808
El Salvador	Non-certified	1 cooperative	25	1.1	100
	Fair Trade	1 cooperative	30	2.3	766
	Organic	1 cooperative	30	3.6	418
	Fair Trade and organic	1 cooperative	11	3.8	275
Nicaragua	Non-certified	1 cooperative	17	1.8	1760
	Fair Trade	2 cooperatives	31	2.7	1111
	Organic	1 cooperative	39	5.1	696
	Fair Trade and organic	1 cooperative	14	3.8	419
Mexico	Non-certified	2 cooperatives	55	2.5	1046
	Fair Trade and organic	3 cooperatives	97	3.2	501
	Totals for the study:	18 cooperatives	469		

[1] For collectively managed cooperatives we recorded the average area allocated per household.

representative cooperatives from a limited pool of organizations that researchers had a relationship with. This limited the strength of our sampling design, and increased the stratification effect, and limited the number of cases within each certification type, which can result in a loss of precision of the statistical analyses[65]. A similar design was also used by the only other quantitative analyses of Fair Trade coffee certification we are aware of[48]. We chose to do this because, due to the sensitive nature of some of the survey questions (e.g., income and food security), it would have been difficult to survey cooperatives that the teams did not know. For organic and Fair Trade certified cooperatives we sought producer organizations with members that had been producing and selling organic and/or Fair Trade coffee for at least 3 years prior to the study. After establishing collaboration agreements with cooperatives, households were randomly selected from lists of cooperative members. As our main criteria, we attempted to sample a target population of between 25 and 30 households per certification type per country (Table 2). However, this proved difficult in some instances, due to a lack of cooperatives that met the criteria (e.g., at the time, there was only one Fair Trade/organic certified cooperative in El Salvador). In total, we collected data from 469 households that were part of 18 cooperatives.

We defined a 'household' as a single or extended family living in the same residence. Household questionnaires were a combination of close-ended and open-ended questions. Household-level data were collected through an identical questionnaire for both certified and non-certified households, except for the additional questions that only pertained to certified households (e.g., certification type, premium amount, etc.). We triangulated this information with individual semi-structured and informal interviews, focus groups with cooperative board members and other key informants (such as personnel from organizations working in the community)[66–68]. Within countries, households were located in different regions, but had similar farm sizes (Table 2). In the case of collective cooperatives in El Salvador, we calculated area allocations per household as equivalent to tenured land-holdings. Considering that the sample consisted of small-scale producers and cooperatives, we expected coffee yields and production practices to be relatively similar across countries and across certifications.

Variable selection, processing and statistical analysis

Variables were selected based on their relevance to household livelihood strategies (e.g., demographics, sources of income, capacities, networks and migration)[51] and those that could demonstrate tangible benefits from certification (e.g., gross coffee revenue, education of children, increased food security and linkages to support networks)[9,41,69]. Although we included questions related to the costs of certification in our survey, we were unable to collect consistent information on this variable at the household level. Most individual members had limited knowledge or confused perceptions, and board members were reluctant to share specific figures.

In cooperatives where land is collectively owned (all three certified cooperatives in El Salvador, and the organic cooperative in Nicaragua), we divided coffee production volumes and land areas under coffee cultivation by the number of cooperative members, in order to obtain volume and land area figures for each household. These figures were used to calculate gross coffee revenue and yield per hectare figures for households in collective cooperatives. While we recognize that these calculations may

not be perfectly accurate (for example, some households may spend more time working in the collective coffee plantation and thus earn more income from coffee), we are confident that they are comparable to the volume, gross revenue and yield figures for the rest of the households in the study.

In order to compare prices, we calculated a weighted average price for each household, because households that sell certified coffee often sell part of their harvest at the certified price and part of the harvest at the conventional price. We calculated weighted price as

(farm gate price for certified organic coffee) *
(% of coffee harvest sold at organic price)
+ (farm gate price for certified Fair Trade coffee) *
(% of coffee harvest sold at Fair Trade price)
+ (farm gate price for conventional coffee) *
(% of coffee harvest sold at conventional price)
+ (farm gate price for certified Fair Trade/organic coffee) *
(% of coffee harvest sold at Fair Trade/organic price)

This more accurately reflected the prices that farmers obtain at the farm gate. Per household gross revenue from coffee sales was calculated as the volume sold per household multiplied by the price received for that volume. In some coffee cooperatives, such as the Fair Trade and organic cooperatives in El Salvador, the coffee plantation is collectively owned. In these cases, gross coffee revenues were divided equally among member households for the purpose of this analysis.

Information was processed into a database created in Foxpro for Windows. Statistical analyses were run using SPSS software, versions 16.0 and 17.0. To analyze the differences in the coffee price, volume, gross revenue and education between certifications, we utilized the Kruskal–Wallis (K–W) non-parametric test. In addition, for coffee price, volume and gross revenue, we used the Mann–Whitney *U* non-parametric test as a *post-hoc* test for differences between each pair of certification types, with a significance level of $P < 0.01$, due to the large number of pairings. The K–W test was also used to analyze factors that might contribute to food security, including a comparison of coffee revenue, food production and number of income sources between households that did and did not experience food shortages. We chose these tests because the data did not show clear normality or equal variances (Levene and Kolmogorov–Smirnov tests), and our household samples were uneven for the certification stratum. We were unable to sample for Fair Trade cooperatives in Mexico, or organic in Guatemala and Mexico, and the number of households sampled for each category were also uneven (see Table 2). The K–W test is a recommended alternative to parametric analysis of variance (ANOVA) for populations containing uneven sample sizes[70]. The K–W test compares medians instead of means; therefore for these variables we report medians and interquartile ranges instead of means and standard deviations. Categorical variables (household savings and credit, food security, and migration) were analyzed using Pearson's chi-square test with $P \leqslant 0.05$ considered significant. For all variables, we compared certifications both for the entire sample and within each of the countries.

Results

Cooperatives and households in coffee regions of Central America and Mexico

We found three types of cooperatives in our research. First-level cooperatives were made up of individual members (individuals and/or families), which organized through different processes, such as agrarian reforms or voluntary initiatives. Within the first level cooperative category, we worked with two different types. The first type comprises cooperatives, consisting of individual farmers/families, who own their land and form a cooperative to facilitate marketing, technical assistance, credit and/or interactions with external actors. These farmers continue to manage their farms individually, but follow cooperative guidelines (e.g., organic certification rules). The second type comprises collectively managed plantations, where members do not have individual ownership of land, but have rights or access to land allocations (i.e., residential and agricultural plot assignations), as part of their membership. These cooperatives are managed as a collective and run by an elected board of directors. The second-level cooperatives were formed by the union of first-level cooperatives. These organizations are also called 'cooperative unions' or 'federations'. The third-level cooperatives may include both first- and second-level cooperatives as members, tend to have national representation and are sometimes called 'confederations'.

On average, the 469 households we surveyed were made up of six members, and had similar educational levels ($\leqslant$5th grade). Men and women were equally represented in numbers, and no significant differences were observed in educational levels by gender. Subsistence agriculture was an important livelihood strategy for farmer households. In El Salvador, 42% of the surveyed group produced staple foods (primarily corn and beans), buying less than 40% of their annual food budget. In the other three countries, only 10% of households reported producing staple foods, and these families bought an average of 65% of their annual food budget.

The mean area of owned or allocated land for coffee cultivation was 3.2 ha per household ($N = 469$). Total mean land areas owned by or allocated to households per country were 5.7, 3.1, 2.9 and 1.5 ha for Nicaragua, El Salvador, Mexico and Guatemala, respectively. Within countries, the farms selected shared comparable geographical conditions. All farms managed shaded plantations of *Coffea arabica*, and were located at elevations greater than 500 m above sea level. Characterizations of coffee producers in

Mesoamerica have found similar yields and outputs as a result of farm size and grower type[71]. Our sample was made up of small-scale farmers and their cooperatives, which according to Flores et al.[71] cultivate less than 3.5 ha of land per farmer and produce an average of 1100 lb ha^{-1}, when coffee is conventionally managed. Average yield for the entire sample (736 lb ha^{-1}) was lower than those presented by Flores et al.[71] (Table 2). Organic yields were lower than conventional yields in Nicaragua and Mexico, but higher in Guatemala and El Salvador. Yields are affected by the management capacity and available resources of farmers and cooperatives. Although data comparisons between organic and conventional coffee yields are scarce, in most cases organic plantations tend to produce lower yields and have similar or higher economic costs[72]. In both El Salvador and Guatemala, the organic cooperatives were larger and had well-established organic management programs that were more effective than their conventional counterparts. In Nicaragua and Mexico, where cooperative management and size were very similar across certifications, organic yields were lower. In these cases, conventional farmers were able to increase yields through effective synthetic fertilizer and pesticide management.

We asked the households we surveyed to list the members of their household who generated monetary income and to list the types of income-generating activities undertaken by household members. Half of the members within each household reported generating monetary income. The most frequent income-generating activities were coffee sales, coffee-related employment, sales of other agricultural crops and non-agricultural employment. Interviewees were asked to estimate the percentage of their income that they earned from coffee sales, coffee-related employment or from other income sources, although not all of them provided complete responses to this query ($n = 300$). On average, households reported that coffee sales and coffee-related employment accounted for 67% of their income. Only 37% reported that they earned all of their income from coffee sales and coffee-related employment. We chose to group coffee sales with coffee-related employment for this analysis because some households in the study are members of collectively owned cooperatives, whereby they do not receive income directly from the sale of coffee but rather are paid by the cooperative for their work in the collective coffee plantation. Sales of other agricultural crops contributed 15% of household income on average, while employment in non-agricultural jobs contributed an average of 11%. Non-coffee agricultural employment and income from other sources (primarily support from older children working away from home) comprised an average of 5 and 3% of household income, respectively.

On average, households sold 1450 lb of coffee for the 2003/2004 harvests. This generated an estimated mean gross coffee revenue of US$1064 for the season. Previous studies have estimated the monetary costs of production for smallholders in this region to range from $0.50 to $0.70 per pound of green coffee produced[71]. However, most cost studies have been incomplete, since they fail to include the costs for coffee maintenance, replanting, tools, harvest interest payments, transport and time invested in inspections and training[73]. Subtracting these estimated minimum farm-level production costs from the gross average price per pound in our sample of $0.78 resulted in an estimated average annual net coffee revenue of between $0.28 and $0.08 per lb of coffee. By applying this net value to the average reported volume sold (1450 lb of coffee per year) by the farmers in our sample, we estimated the net coffee revenue per household per year to be in the range between $116 and $406. This range is for the entire sample and not accounting for differences in revenues between certifications. However, it represents an important figure because it shows how low the annual revenue range from coffee production is for all of these farmers, including those that sell all their volumes through certified channels.

Farmers generally do not receive payments for all their coffee in one lump sum. Instead, some receive advance payment as credit, partial payment upon coffee delivery and a third final payment. Most receive a single payment when they sell to intermediaries. Most payments are both insufficient and poorly timed, leaving a thin (or hungry) season that generally falls between April and August for most coffee regions.

Only 15% of all households interviewed reported having monetary savings, these being most frequent in Nicaragua, and least frequent in El Salvador. In Guatemala and Mexico, 15 and 16% of households reported having some savings. Forty percent of all households reported having access to some form of credit, with a marked difference between countries. Approximately 34% of households in the four countries reported at least one member migrating, either within their countries, or internationally. Mexico (in 30.6% of the sample) and Nicaragua (28.8%) had the highest emigration rates of the sample.

Coffee prices, volumes and gross revenue

Gross coffee revenue is determined by three factors: price, total volume (green bean yields) and the proportion of volume that is sold through certified channels (and thus receives the certified price). We first examined how certified cooperatives differ from non-certified cooperatives with respect to each of these factors and then look at the resulting differences in gross revenue.

Annual international conventional (non-certified) coffee prices averaged $0.72 lb^{-1} in 2003/2004[3]. As reported in similar studies, it proved extremely difficult to calculate exactly what price households obtain for their coffee[23]. The different ways in which coffee is sold and the taxes and discounts that occur in each country were not fully understood by many of the farmers. To compare the prices

Table 3. Price, volume and coffee revenue medians (interquartile ranges)[1] for conventional and certified coffee, as reported by all interviewed households in Mexico and Central America ($N = 461$).

	Non-certified ($n = 124$)	Fair Trade ($n = 98$)	Organic ($n = 68$)	Fair Trade/organic ($n = 175$)	K–W test[4]
Median calculated price[2] (US$ lb^{-1})	0.51 (0.24)[3a]	0.68 (0.32)[b]	0.77 (0.36)[c]	0.89 (0.32)[c]	$\chi^2 = 186.98$, $P \leqslant 0.001$**
Median volume in pounds	700 (1300)[a]	1094 (1100)[b]	3550 (3048)[b]	600 (900)[a]	$\chi^2 = 51.1$, $P \leqslant 0.001$**
Median coffee revenue in US$	332.56 (800.06)[a]	1006.48 (635.80)[b]	2733.50 (2164.01)[c]	534.00 (818.16)[a]	$\chi^2 = 55.78$, $P \leqslant 0.001$**

[1] The K–W test uses medians, and the figures in parentheses are interquartile ranges (analogous to standard deviation for the median).
[2] The calculated price is the median price a household received for their coffee in 2003–2004, weighted by the volumes sold at those prices.
[3] Medians followed by a different letter are significantly different by the Mann–Whitney U test ($P \leqslant 0.01$).
[4] * Difference is significant at the $P \leqslant 0.05$ level; ** difference is significant at the $P \leqslant 0.001$ level.

Table 4. Median prices (interquartile ranges)[1] by certification and country ($N = 461$).

Country	Median non-certified calculated price[2] (US$ lb^{-1})	Median Fair Trade calculated price (US$ lb^{-1})	Median organic calculated price (US$ lb^{-1})	Median Fair Trade/organic calculated price (US$ lb^{-1})	K–W test[5]
Guatemala	0.48 (0.95)[3a], $N = 30$	0.64 (0.65)[b], $N = 30$	—	0.81 (0.11)[c], $N = 57$	$\chi^2 = 95.81$, $P \leqslant 0.0001$**
El Salvador	0.51 (0.00)[4a], $N = 25$	0.92 (0.00)[4b], $N = 30$	1.13 (0.00)[4c], $N = 30$	1.06 (0.00)[4d], $N = 11$	$\chi^2 = 70.52$, $P \leqslant 0.001$**
Nicaragua	0.38 (0.39)[a], $N = 17$	0.54 (0.20)[a], $N = 31$	0.77 (0.00)[4b], $N = 38$	1.07 (0.00)[4c], $N = 14$	$\chi^2 = 70.52$, $P \leqslant 0.001$**
Mexico	0.70 (0.27)[a], $N = 52$	—	—	1.11 (0.36)[b], $N = 93$	$\chi = 37.30$, $P \leqslant 0.001$**

[1] The K–W test uses medians, and the figures in parentheses are interquartile ranges (analogous to standard deviation for the median).
[2] The calculated price is the median price a household received for their coffee in 2003–2004, weighted by the volumes sold at those prices.
[3] Medians followed by a different letter are significantly different by the Mann–Whitney U test ($P \leqslant 0.01$).
[4] Coffee is produced and sold cooperatively; thus all households in these cooperatives receive the same median price.
[5] * Difference is significant at the $P \leqslant 0.05$ level; ** difference is significant at the $P \leqslant 0.001$ level.

presented in Table 3, we used information gathered through household surveys and data from first- and second-level cooperatives.

Calculated prices (the sum of the amount of coffee sold at each price, multiplied by the % of total coffee sold at this price) were significantly higher for all certified sales in comparison to conventional markets (K–W, $\chi^2 = 186.98$, df = 3, $P \leqslant 0.0001$), with Fair Trade/organic cooperatives receiving the highest price (Table 3). Price differences between each pair of certifications individually were also significant except between the organic and Fair Trade/organic groups (Table 3).

Significant price differences (for both conventional and certified) were also observed between countries (K–W, $\chi^2 = 60.3$, df = 3, $P \leqslant 0.001$), so it is possible that the comparison between certifications was confounded by the uneven representation of cooperative types in the four countries. Thus, we also compared certified and non-certified cooperatives within each of the countries, through a Mann–Whitney U test. There were significant differences in calculated price between certification types in all of the countries, with households that were members of certified cooperatives receiving higher prices for their coffee (Table 4). Only in the Nicaraguan case were conventional and Fair Trade prices not significantly different. Because certification types were only represented by members from one cooperative in several of the countries, we cannot state conclusively that certifications were solely responsible for these price differences, as other factors unique to these cooperatives may have contributed to the differences in price. However, because price premiums are generally based on certifications, it is likely that certifications are driving these price differences.

Volumes of coffee produced and sold were highly variable between households. Fair Trade and organic certified households produced significantly more coffee than non-certified households or households holding both certifications (Table 3; K–W, $\chi^2 = 51.10$, df = 3, $P \leqslant 0.001$). It is important to note that these are total volumes, not volumes per area, and they are therefore more reflective of farm

areas per household than per hectare productivity. The organic households and Fair Trade households in this study tended to cultivate more land per household than the other two certification groups, which accounts for the higher coffee volumes of the organic households despite their lower per hectare productivity in Nicaragua and Mexico.

Gross revenue from coffee was significantly different between households of the four certification types (K–W, $\chi^2 = 55.78$, df = 3, $P \leqslant 0.0001$), with all certification groups earning higher median revenues than the uncertified group (Table 3). Gross revenues were also significantly different between certification groups when analyzed by country, with the exception of Mexico where revenues in the Fair Trade/organic households were similar to those in the non-certified households due to lower coffee production volumes (Table 5).

As discussed by Bacon[23], certified farmers are usually not able to sell all of their production through certified markets. Reasons for this include quality standards (only the best cherries), limited market demand (as in the case of Fair Trade) and cooperative quotas (e.g., distribution of premiums among the membership). As a result, many certified coffee farmers are forced to sell a portion of their production in the conventional market. Net revenue generated through certified sales can decrease considerably when farmers incur the costs of certification, but are not able to sell their entire production at premium certified prices.

Various factors influence the percent of production that households in certified cooperatives are able to sell at certified prices. The Salvadoran Fair Trade cooperative was able to sell all of its production at certified prices because of the small number of Fair Trade certified cooperatives in this country that produce high-quality coffee. In the Guatemalan and Nicaraguan cases, Fair Trade certified cooperatives were limited by a higher number of Fair Trade cooperatives and higher volumes of production by certified farms. Thus, most of these households sold high proportions of their coffee at conventional prices. Fair Trade/organic certification showed high proportions of volumes sold at certified prices in all cases, with the exception of Mexico (only 54%). In this case, where farmers were members of large cooperative unions (up to 20,000 members), the amount of coffee sold at certified prices was influenced by coffee quality and the standing of first-level cooperatives within their union. A power struggle was reported between first-level cooperatives and their unions, in which their lobbying capacity with the union is an important factor determining the proportions of their total production that they are able to sell at certified prices.

On average, Fair Trade was the certification with the lowest proportion of coffee sold at certified prices, with 60% of total volume sold as Fair Trade. The two certified organic cooperatives sold almost 100% of their certified coffee at certified prices. Fair Trade/organic certification

Table 5. Household coffee revenue medians (interquartile ranges)[1] by country and certification ($N = 461$).

Country	Median non-certified revenue (US$)	Median Fair Trade revenue (US$)	Median organic revenue (US$)	Median Fair Trade/organic revenue (US$)	K–W test[3]
Guatemala	271.84 (389.25)[2a], $N = 30$	603.13 (1030.85)[b], $N = 30$	—	534.00 (795.65)[b], $N = 57$	$\chi^2 = 13.862$, $P \leqslant 0.001$**
El Salvador	102.50 (384.38)[a], $N = 25$	1006.48 (0.00)[b], $N = 30$	569.49 (0.00)[c], $N = 30$	1040.92 (471.43)[c], $N = 11$	$\chi^2 = 56.66$, $P \leqslant 0.001$**
Nicaragua	752.80 (2668.26)[a], $N = 17$	2158.00 (2120.00)[ab], $N = 31$	2733.50 (228.62)[b], $N = 38$	1076.57 (2170.50)[a], $N = 14$	$\chi^2 = 8.68$, $P \leqslant 0.034$*
Mexico	561.09 (937.89)[a], $N = 52$	—	—	445.65 (899.46), $N = 93$[a]	$\chi^2 = 0.474$, $P \leqslant 0.491$

[1] The K–W test uses medians, and the figures in parentheses are interquartile ranges (analogous to standard deviation for the median).
[2] Medians followed by a different letter are significantly different by the Mann–Whitney U test ($P \leqslant 0.01$).
[3] * Difference is significant at the $P \leqslant 0.05$ level; ** difference is significant at the $P \leqslant 0.001$ level.

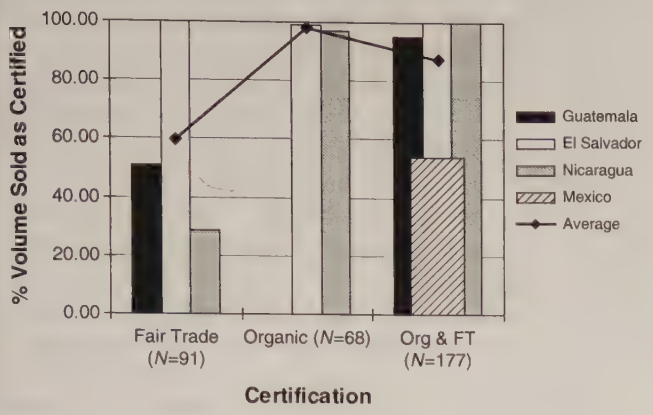

Figure 1. Percentage of total volume of coffee produced by certified households, which was sold through certified channels, for the 2003/2004 harvest.

sold an average of 87% of total coffee produced at certified prices (Figure 1).

Household savings and credit

Households in our survey population were asked whether or not they had any monetary savings. While it is generally uncommon for small-scale coffee-producing households to have savings, the percentage of certified households with savings (17%) was significantly higher than the figure for non-certified households (10%) when all certified households were combined into a single category (Pearson, $\chi^2 = 4.113$, df = 1, $P \leqslant 0.043$). This difference, however, was influenced by the households in the Fair Trade co-operative in Nicaragua, where 55% of respondents reported having savings. This is a much higher percentage than any of the other certified groups and countries. There were no significant differences between certified and non-certified households in any of the other countries.

Credit access showed a similar pattern as savings; however, the association between credit access and certification when all certified households were combined into a single group was not quite statistically significant (Pearson, $\chi^2 = 3.26$, df = 1, $P \leqslant 0.073$). Overall, 43% of all certified households reported having access to credit, compared to 34% of non-certified households. When certification types were considered separately, however, there was a significant association between certification type and credit access (Pearson, $\chi^2 = 9.81$, df = 3, $P \leqslant 0.020$). Higher percentages of Fair Trade (42%) and Fair Trade/organic (48%) households reported having access to credit than organic (30%) and non-certified households (34%). This is not surprising given that Fair Trade contracts often include pre-financing for producers, whereas organic and conventional coffee buyers do not provide this benefit. This pattern held when each of the countries was examined separately, with the exception of Guatemala where nearly all of the non-certified households reported having access to credit.

Food security

Household food security has been used extensively as a measure of welfare by NGOs, governments and the UN. At the 1996 World Food Summit, the Food and Agriculture Organization of the United Nations defined food security as 'all people, at all times, have physical and economic access to sufficient safe and nutritious food to meet their dietary needs and food preferences for a healthy and active life'[74]. Food security results from many livelihood factors, including food production, income to purchase food and social safety nets[75].

To explore the issue of food security, we asked families if they experienced times when they felt unable to meet their basic food needs. Sixty-three percent of the households interviewed reported that they did struggle to meet their basic food needs. In our sample, households associated with certifications did not fare any better in terms of food security. Our statistical analyses of the entire sample showed significant associations between food security (using household's reports of difficulties in meeting basic food needs as a proxy) and certification, but with a higher percentage of households in all *certified* groups reporting difficulties meeting food needs (Pearson, $\chi^2 = 22.06$, df = 3, $P \leqslant 0.001$) than the non-certified group. When each country was examined separately, only in Guatemala was there a significant association between certification and food security (Pearson, $\chi^2 = 21.78$, df = 2, $P \leqslant 0.001$), again with more certified households reporting difficulties meeting their food needs.

We also asked households to estimate what percentage of their food they produced on farm and what percentage they purchased. There was no significant association between certification and self-sufficiency in food production (K–W, $\chi^2 = 0.246$, df = 1, $P \leqslant 0.620$), with all certification groups purchasing the majority of their food. On average, households purchased 61% of their food. We recognize, however, that food production is only one livelihood factor that may contribute to food security. To tease out some of the reasons why households may or may not be able to meet their food needs, we also examined the relationships between reported ability to meet food needs and gross coffee revenue and number of income sources. There was no significant difference in median gross coffee revenue between those households that did and did not report difficulty meeting their food needs (K–W, $\chi^2 = 0.16$, df = 1, $P \leqslant 0.690$). Having more sources of income was, however, associated with being able to meet food needs (K–W, $\chi^2 = 7.97$, df = 1, $P \leqslant 0.005$). Households that did not experience food shortages reported an average of 2.5 income sources, compared with an average of 2.2 income sources for households that did report food shortages.

Education

We measured differences in educational levels by the percent of school-age children in a household that were

reported to be currently in school. Children were defined as of school age if they were over 6 and under 18 years old. We focused on the current education status of children because coffee certifications are relatively new, and could not be expected to affect the educational outcomes of adults[48]. The median for all certification types was approximately 50% of school-age children in school, with no significant difference between certification types (K–W, $\chi^2 = 1.94$, df = 3, $P \leqslant 0.58$). In none of the four countries did the percentage of school-age children per family attending school differ significantly between certification types and non-certified households.

Migration

Migration can be viewed as a plausible strategy that rural households undertake to support their livelihoods by generating income outside of the region. However, some authors argue that migration can have negative effects on rural communities, as it eventually leads to a depletion of human capital, which is necessary to reproduce existing livelihoods[76,77]. In the case of Fair Trade/organic coffee, some studies and certification advocates have suggested that certification has led to decreased migration from coffee regions[77]. Hence, our main research objective related to migration was to examine if certified cooperatives were experiencing a lower incidence of migration than uncertified farmers. To analyze the effects of certification on emigration, we compared the percentages of households from whom at least one family member had emigrated between certified and non-certified groups. 'Emigration' was defined as leaving the home community in order to work. There was some association between certification and emigration when certification types were compared individually, with 37% of non-certified households, 31% of Fair Trade households, 48% of organic households and 27% of Fair Trade/organic households having had a member migrate (Pearson, $\chi^2 = 11.01$, df = 3, $P \leqslant 0.12$). However, when all certification types were combined into one group, there was no significant association between certification and migration (Pearson, $\chi^2 = 0.92$, df = 3, $P \leqslant 0.34$). Neither was there any clear association when the data were examined on a country-by-country basis. It is unlikely that certifications were contributing to any differences in emigration in our sample.

Participation in social and support networks

Through social networks, which can range from the local to the international, individuals, households and communities can expand their access to resources and other opportunities[78]. For example, Fair Trade certified cooperatives in El Salvador received important donations from organizations associated with Fair Trade during the 2003 earthquakes[79]. In our sample, households reported being linked with at least the six following types of support organizations or networks: (i) first-level cooperatives; (ii) second-level cooperatives; (iii) national organizations or institutions, including NGOs and government institutions; (iv) international organizations or institutions, including NGOs and donors; (v) religious groups, mostly Evangelical and Catholic church groups; and (vi) local/community groups and committees. Households from Fair Trade/organic cooperatives most frequently reported association with organizations and networks. These households cited second-level cooperatives most frequently (50%), followed by national (46%) and international organizations (44%). Both conventional and Fair Trade households cited international organizations most frequently (26 and 28%, respectively), while certified organic cooperatives cited national organizations most frequently (27%).

Knowledge of certification, accountability and power dynamics

We found that there was still much confusion among farmers and cooperative members about what certifications are, and cooperative member's understanding of what it means to 'be certified'. This has also been documented in previous studies[9], and was consistent with the data provided by all of the certifiers and some of the other actors interviewed. In general, farmers understood organic certification much better than Fair Trade. Organic has clear regulations regarding agricultural practices, which farmers found easy to comprehend. Understanding Fair Trade is more challenging, since its standards are based on notions of justice and empowerment[23,80]. On the other hand, certifications were better understood by board members of first-level cooperatives, and fully understood by staff and board members of second-level cooperatives.

Discussion

Effects of certifications on household livelihoods

Most studies on coffee certifications support our results that Fair Trade, organic or Fair Trade/organic certified cooperatives obtain higher coffee prices. Examples of this research include work in Nicaragua[23,80,81], Guatemala[9], Mexico[9,40,41,43] and El Salvador[46]. Price differences were also observed between countries, which relate to the quality of the coffee (as measured by cupping), but also to 'symbolic quality' associated with the marketing of a 'country' brand or image[61]. Households generally have very little control over these quality factors.

Certifications had a positive effect on the incidence of household savings, especially in the Nicaraguan Fair Trade cooperative. Fair Trade and Fair Trade/organic certifications improved credit access, although credit was usually in the form of pre-financing for coffee and not in the form of loans to households. This is consistent with other studies reporting that Fair Trade/organic certification improves credit access and financial stability for cooperative organizations[23,37,41], although not necessarily

for households. Our research suggests the need for follow-up studies around food security issues, since most households claimed they suffered food shortages. The findings also showed that certified households reported more difficulties in meeting basic food needs than non-certified households. Although certified households earned higher gross coffee revenue, this did not translate to greater food security, possibly due to the higher production costs associated with certified production, or with the timing of payments for coffee production (which usually does not coincide with the 'thin months' between staple crop harvests—June to August). Having more than one income source (i.e., not relying entirely on coffee sales for income) did, however, contribute to household food security, perhaps by providing a year-round income source. A comprehensive investigation of all aspects of food security was beyond the scope of this study, and it is possible that other measures of food security (e.g., frequency of skipping meals) would yield different results. Additional research is needed to understand all dimensions of food security, including local contextual factors, in order to begin unpacking the proximate and root causes among all coffee-producing smallholders. No differences were found in the educational levels of school-age children attending school between certified and non-certified households.

We found no differences in the level of migration of certified and non-certified households. These results differ from two different studies in Oaxaca, which found that the higher prices derived from certified coffee sales allowed households to incur the expenses necessary for members to migrate[42]. An ethnographic study by Jaffee[41] also reported that the outmigration of household members affiliated to cooperatives selling to Fair Trade certified markets was twice as high as the figure for non-certified households. However, the heads of households were less likely to migrate among households connected to Fair Trade.

Social networks are an important asset for rural households in developing countries[37,51,82]. These connections and affiliations help farmers obtain important support from government and non-government actors and provide access to knowledge and capacity building[6]. Our data showed that Fair Trade/organic certified households had higher access to different types of networks than other certifications and non-certified cooperatives, although these data were not analyzed statistically. Similar reports confirm the role of coffee certifications in expanding support networks in El Salvador, Nicaragua and Mexico[37,40,66].

Power dynamics in the coffee value chain

Lack of understanding of certification meanings and standards at the household level, especially for Fair Trade, is a persistent problem that has been repeatedly reported in the literature and confirmed by our research[9,46,80]. However, relatively little research has focused on this topic. More attention has been focused on the power dynamics between national and international certifiers and cooperatives in coffee certified networks[5,44,83]. It is clear from our research that certifications can work well for certain types of cooperatives (e.g., highly organized, high-quality coffee, etc.), but may not be a good option for others. Thus, comprehending the opportunities and limitations of certifications is the first step for farmers to make an informed decision regarding their participation in these types of networks. In our sample, the knowledge and understanding to make the right decisions regarding certifications were missing at the household level.

The predominantly buyer-driven coffee value chain is able to enforce a degree of accountability as producer organizations respond to the demands on the northern part of the chain (i.e., importers, roasters, retailers and certification agencies)[61]. Yet, these producers have few mechanisms for holding buyers accountable[6]. In addition, keeping farmer organizations accountable to their members has also been a long-standing challenge[84] and an increasing preoccupation for stakeholders at the processing (i.e., roasters) and consuming ends of the coffee chain[60]. We found clear concerns related to accountability, lack of transparency and miscommunication between households, cooperatives and unions. This is further complicated by the fact that certification systems can have complex repercussions on the social dynamics of cooperatives and their interactions with member households and other community stakeholders[44]. These can range from cooperative or community members obtaining direct benefits, such as inspector wages, to the tension that can arise when local inspectors find members that are not meeting required certified standards[85].

Conclusions

Effects of certifications

Our study corroborated the conditions of economic poverty among small-scale coffee farmer households in Central America and Mexico[4,86]. All certifications provided a higher price per pound and higher gross coffee revenue than non-certified coffee. However, the average volumes of coffee sold by individual households were low, and many certified farmers did not sell their entire production at certified prices. This meant that the revenue contribution of coffee sales to household livelihoods was relatively small, regardless of certification. In addition, certifications had insignificant effects on other livelihood-related variables, such as education, and incidence of migration at the household level, although they were positively associated with savings and credit. The combined Fair Trade/organic certification also linked farmers with a higher number and diversity of support networks, a factor that was considered important by all farmers interviewed. As a market mechanism, certification is working effectively by providing better prices for certified coffee, but the contribution derived from these premiums has limited effects on household livelihoods. This demonstrates that certifications alone will

not bring significant poverty alleviation to most coffee families.

Policy recommendations

The relatively small average volumes of coffee produced by most small-scale farmers, and the even lower volumes that they are able to sell at certified prices, point to the need to support livelihood and agricultural diversification in coffee areas[9,87]. These initiatives should be 'related to, but separate from coffee', as was expressed by Salvadoran coffee farmers in a focus group in 2002[88]. Food security remains precarious in most of the households interviewed, which justifies this as a priority area of investment for development interventions in coffee areas. Recent trends in global food prices and availability further support this argument.

Until now, a high level of investment by donors and development organizations has been placed in facilitating second-, and to a lesser degree, first-level cooperatives to acquire Fair Trade and organic certifications and markets[23]. While this has certainly helped build the capacity of cooperatives, our data suggest that some of this support could be re-directed to establish higher accountability within cooperatives and to increase knowledge and decision-making capability related to diversification strategies. This will require investments that are more locally based and less directed towards superficial monitoring of second- and third-level cooperative unions. Misunderstanding of prices, terms and benefits from certifications by both farmers and first-level boards of directors is also a long-standing problem with certifications. This is related to inefficient capacity building, complicated price and credit structures and lack of transparency within some cooperative organizations. Much improvement can be achieved by designing efficient popular educational materials and training approaches on certifications that are adequate for the educational levels of coffee farmers (see Méndez[89]).

Although we have argued that certified coffee markets alone will not resolve the livelihood challenges faced by smallholder households, they could still contribute to broad-based sustainable livelihoods, rural development and conservation processes in coffee regions. This can be done by developing more active partnerships between coffee farmers, certifications and environmental and rural development organizations and researchers[86]. Certifications, especially Fair Trade/organic, have proven effective in supporting capacity building and serving as networks that leverage global development funding for small-scale coffee-producing households. These community level investments should focus on livelihood diversification directed at alleviating the persistent livelihood vulnerabilities of smallholder coffee farmers identified in this and other studies[9,41,48,86].

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Book Review

Plan B 4.0: Mobilizing to Save Civilization. By Lester R. Brown. W.W. Norton and Co., New York, NY. 368 p., paper, $16.95, ISBN 978-0-393-33719-8.

With an incredible level of energy and unwavering focus over the horizon, Lester Brown never ceases to amaze his readers with yet another annual greenprint for the future. *Plan B 4.0: Mobilizing to Save Civilization* is the update of his new approach begun in 2006 with the first *Plan B*. With a shrewd economist's eye on the present and a futurist's vision of what is over the hill, Dr Brown provides us with a summary of contemporary challenges as well as feasible options on how to solve them. This is a must-read book for those who are serious about development and the future of our species.

Aptly titled 'Selling Our Future', the first chapter opens with a brief historical look at prior civilizations, and speculates that, in spite of our sophisticated technologies and global communications, we have not solved the dual challenges of financial stability and food equity. He cites three trends as key to growing shortages of grains to sustain us: increasing population, growing protein consumption and more bio-based fuels. Food security is further challenged by soil erosion, depletion of major freshwater supplies and climate instability. Insecurity in the world grain trade emerges as a consequence of geopolitical struggles, with national limits or bans on exports and the land rush by outsiders to acquire productive areas in Africa. In a bold listing of *failed states*, Dr Brown chronicles the combination of overpopulation with respect to available resources that will make it impossible for many countries to solve the hunger problem on their own. As with previous editions, *Plan B 4.0* to some extent discounts the potential of new technologies to allow us to continue current lifestyles. Fortunately, there are current solutions available based on present technology, but they must be implemented in a massive way, and it must be done now.

The pressure that our growing human population puts on available soil and water resources is documented in Chapter 2 with a series of specific examples of land loss and degradation as well as declining water tables in some areas that have provided a foundation for the advances of the Green Revolution. Competition for scarce water by cities and by industry demonstrates how these immediate needs outweigh farmers' ability to access water for food production, a short-term but serious complication that will last until many people are truly hungry. Loss of productive land and natural resources is causing a new class of what Dr Brown calls *environmental refugees*, people squeezed out by encroaching deserts or dropping aquifers. Most of the author's descriptions of declining resources would cause a little debate in any circles.

Continuing doubts about climate change are addressed by the evidence in Chapter 3. For example, such biological realities as the plateau of photosynthesis at 20°C and the increase in respiration beyond that point lead to reduced crop yields, one consequence of global warming. Thus it is not only the increasing CO_2 content and greater potential for greenhouse effect, nor the melting of glaciers and rising seas that threaten our food supply, but also the larger disruption of terrestrial ecosystems due to the increasing climatic instability and reduction in global potential for food production.

A series of responses to this emerging reality are proposed, including an improved efficiency of energy use through design and conservation (Chapter 4), a major shift to renewable energy (Chapter 5), better design of cities for reducing energy and water use (Chapter 6), confrontation of the population issue through education (Chapter 7) and renewal of the Earth and its resources through restoration of forests, grasslands and oceans and their attendant biodiversity (Chapter 8). Of greatest immediate interest to those in agriculture is the focus in Chapter 9 on creating adequate nutrition for our current and future populations. Given that most potentially productive lands are already under cultivation, we have no choice but to increase productivity of current farmland. Yields of major cereals have leveled, wheat at 7 metric ton ha^{-1}, rice at 5 metric ton ha^{-1} and maize at 10 metric ton ha^{-1}. Only with extraordinary and often non-profitable application of fertilizers and other inputs can we push production above these levels, and the response per unit of inputs has declined drastically for the past two decades. We have maxed out on the potential for irrigation and must now learn to use our finite water resources much more efficiently. The demand for animal protein must take into account the differences in conversion efficiency from kg of feed to kg of meat produced by beef (7 : 1), swine (3 : 1), poultry (2 : 1) and fish (< 2 : 1). There is growing recognition of the efficiency of local food systems, a future priority that is in direct contrast to the recent move toward globalization. Important to educators in agriculture is the need for a food system that moves consumers down the food chain, reduces the use of grain to fuel vehicles and elicits essential attention to the human population factor in the global food picture. Since these directions all go against the grain of current society in most countries and they move into areas that most instructors would rather not touch in courses in agriculture, it will take courage and commitment for those in education to embrace a new paradigm for the food system.

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In the concluding Chapter 10, 'Can We Mobilize Fast Enough', Lester Brown presents the challenge as an essential implementation of massive change through Plan B. Four goals are: 'stabilizing climate, stabilizing population, eradicating poverty and restoring the economy's natural support systems', all of which are critical to reaching any semblance of global food security. Although a firm believer in capitalism, the author quotes Norwegian Østein Dahl, the former vice president of Exxon: 'Socialism collapsed because it did not allow the market to tell the economic truth. Capitalism may collapse because it does not allow the market to tell the ecological truth.' Some of the components of a path toward a sustainable future include raising taxes on destructive activities such as fuel consumption, cigarettes and carbon-generating activities; phasing out coal and moving toward renewable, clean energy sources; shifting toward more energy-efficient transportation; and recognizing key tipping points in resource availability and environmental indicators. Brown cites the need for a mobilization that is similar to what was achieved in war time, one that will not be possible without significant change in social attitude toward both the current status quo and what will be needed in the future. While other authors are more optimistic about reduced consumption through social change, Brown comes across as a realist who thinks it will take a large wake-up call to make things happen.

Three models are suggested that could precipitate essential change. The *catastrophic model* is exemplified by Pearl Harbor, an event that changed how people in the USA thought about war. Although a powerful model, to wait for catastrophe is often to wait too long to change behavior, with the example of how carbon emissions are undermining the West Antarctic and Greenland ice sheets and when seas rise by several feet it will be too late to change. The *tipping point model* refers to the gradual buildup of evidence about problems that suddenly become evident and precipitate rapid change. The example is evidence about cancer caused by smoking, and the immediate impacts of accumulated scientific experience on smoking rates, medical costs to society and large court settlements against manufacturers that caused large changes in behavior. The preferred alternative is the *sandwich model* that brings potential for relatively rapid social change. As an example, recognition of the need to reduce carbon emissions caused a shift away from burning coal, a move toward more fuel-efficient vehicles, a rapid growth of wind and solar energy technologies and consciousness about the critical need for energy conservation. These trends are all emerging as important in the USA and across the globe.

To implement *Plan B 4.0*, Lester Brown proposes that we need a quantum change in economic and political attitude and that we need to look carefully at where resources are invested. He estimates the annual costs of major needed global changes at $10 billion for universal education, $4 billion for adult literacy based on volunteer teachers, $33 billion for basic health care in developing countries, $17 billion for reproductive health care and family planning, $3 billion for preventing spread of AIDS virus, $6 billion for school lunch programs in the 44 poorest countries and $4 billion for assistance to preschool children and pregnant women. The total of $77 billion to provide these basic social services is only about 5% of the current annual global military budget of $1464 billion. In another striking comparison, Dr Brown calculates the annual cost of planting trees to conserve soil and sequester carbon, protecting cropland soils, restoring rangelands and fisheries, protecting biodiversity and stabilizing water tables at $110 billion, or just under 8% of the annual global military expenditures. He poses this final question: Can we afford not to undertake these social and environmental priorities? And comparing this expense to that of military equipment and operations, which will more likely lead to a sustainable future world society?

Charles Francis, 279 Plant Science, University of Nebraska, Lincoln, NE 68583-0915, USA. email: cfrancis2@unl.edu
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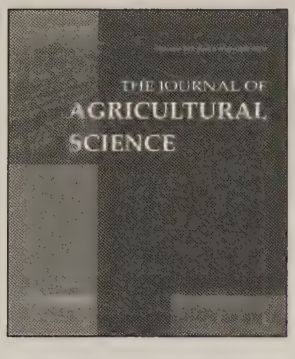

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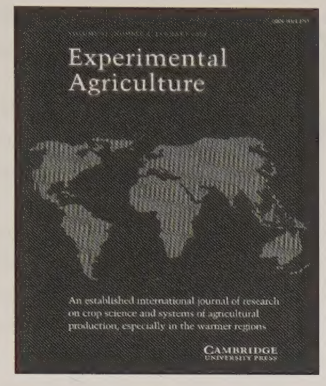
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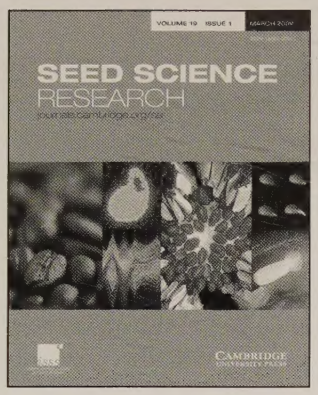

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2. Brink, R.H. Jr, Dubach, P., and Lynch, D.I., 1960. Measurement of carbohydrates in soil hydrolyzates with anthrone. Soil Science 89:157–166.
3. Greenland, D.J., and Szabolcs, I., (eds). 1994. Soil Resilience and Sustainable Land Use. CAB International, Wallingford, UK.
4. Arshad, M.A., and Coen, G.M., 1992. Characterization of soil quality: Physical and chemical criteria. American Journal of Alternative Agriculture 7:25–31.
5. Coale, F.J. 1996. Descriptions of the soil test interpretive categories used by the University of Maryland Soil Testing Laboratory. SFM-3. University of Maryland, College Park.

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